ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSISTANT EDITORS

H. E. MCKINSTRY, *Harvard University*
F. M. CHACE, *U. S. Geological Survey*
JOE W. PEOPLES, *Wesleyan University*
J. D. BATEMAN, *Yellowknife, N.W.T.*
R. H. JAHNS, *California Institute of Technology, Pasadena*

ASSOCIATE EDITORS

CHARLES KENNETH LEITH
University of Wisconsin, Madison, Wis.

D. F. HEWETT
U. S. Geological Survey, Washington, D. C.

A. I. LEVORSEN
Department of Geology, Stanford University, Calif.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
U. S. Geological Survey, Washington, D. C.

A. N. SAYRE
U. S. Geological Survey, Washington, D. C.

L. C. GRATON
Harvard University, Cambridge, Mass.

E. S. MOORE
Royal Ontario Museum, Toronto, Can.

PER GEIJER
Geological Survey of Sweden, Stockholm, Sweden

P. F. FOURMARIER
Liège University, Liège, Belgium

M. S. KRISHNAN
Geological Survey, Calcutta, India

DJALMA GUIMARÃES
Instituto de Tecnologia Industrial Belo Horizonte, Minas Gerais, Brazil

T. W. GEVERS
University of the Witwatersrand, Johannesburg, S. Africa

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1951

IRA B. JORALEMON.....*President*
ANTON GRAY.....*Vice President and President elect*
MORRIS M. LEIGHTON *Past President*
DONALD M. DAVIDSON *Vice President elect*

OLAF N. ROVE.....*Secretary*
U. S. Geological Survey, Washington 25, D. C.

JOSEPH T. SINGEWALD, JR...*Treasurer*
Johns Hopkins Univ., Baltimore, Md.

Councilors

1951	*1952*	*1953*
PHILIP J. SHENON	H. M. BANNERMAN	HARRISON A. SCHMITT
ANDREW LEITH	JOHN S. BROWN	LLOYD M. SCOFIELD
JOHN GUSTAFSON	CHARLES F. PARK, JR.	C. O. SWANSON

Regional Vice-Presidents

H. C. GUNNING, North America....GUILLERMO ZULOAGA, South America
MICHEL LEGRAYE, Europe.....JOHN L. FARRINGTON, Africa
M. S. KRISHNAN, Asia.....J. M. RAYNOR, Australia

Executive Committee

IRA B. JORALEMON, *Chairman* H. G. FERGUSON MORRIS M. LEIGHTON
ANTON GRAY OLAF N. ROVE JOSEPH T. SINGEWALD, JR.

Finance Committee

WILLIAM CALLAHAN, *Chairman* W. O. HOTCHKISS T. B. NOLAN
JOSEPH T. SINGEWALD, JR.

Program Committee

F. S. TURNEAURE, *Chairman* DONALD M. DAVIDSON OLAF N. ROVE
CARL FRIES JOHN K. GUSTAFSON

Committee on Publications

EUGENE N. CAMERON, *Chairman* EDWARD L. CLARK H. E. MCKINSTRY

Nominating Committee

CHARLES F. PARK, JR., *Chairman* H. M. BANNERMAN GEORGE M. FOWLER

Admissions Committee

PHILIP J. SHENON, *Chairman* HAROLD M. BANNERMAN FREDERICK C. KRUGER
HARRISON A. SCHMITT FRANK EBBUTT

Auditing Committee

FRANCIS G. WELLS, *Chairman* A. NELSON SAYRE

Coal Research Committee

Executive Members: Walter V. Searight, *Chairman*, Paul Averitt, Clayton G. Ball, G. H. Cady

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 46 MAY, 1951 No. 3

THE URANIUM DEPOSITS NEAR MARYSVALE, PIUTE COUNTY, UTAH.[1]

JOHN W. GRUNER,[2] WALLACE G. FETZER,[3] AND IRVING RAPAPORT.[4]

ABSTRACT.

The uranium deposits are ore zones in igneous rocks chiefly in an intrusive of quartz monzonite. The zones consist of quartz-fluorite-calcite-pyrite veins and veinlets commonly of similar strike and dip. Pitchblende occurs as very thin seams or as grains in and between the veins. Weathering extends to at least 200 feet and has resulted in secondary schroeckingerite, autunite, torbernite (and their meta modifications) and a uranophane-like mineral. The mineralization is of late Tertiary age.

INTRODUCTION AND ACKNOWLEDGMENTS.

THE announcement in June 1949 of the discovery of uranium ores about 3 miles north of Marysvale, Utah, caused a rush of prospectors to this region. The provoking feature about these deposits is that they occur in an area of volcanic and plutonic igneous rocks of Tertiary age. In other words, they are in no way related to the well-known Colorado Plateau deposits that occur in sedimentary rocks. These volcanic rocks have been studied in some detail by Eugene Callaghan.[5]

The Marysvale area in south central Utah lies between the Tushar Range to the west and the Sevier Plateau to the east in a transverse range of hills known as Antelope Range (Fig. 1). The outlines of the volcanic and Plutonic series, as given by Callaghan, are shown in Figure 2. The detailed work on the deposits was under the direction of the Atomic Energy Commission, Raw Materials Operations Offices. We are indebted to these men for permission to publish this paper. We also enjoyed the kind cooperation of all the mining

[1] Presented at the Geological Society of America Meeting, Washington, D. C., November 16, 1950.

[2] University of Minnesota.

[3] Formerly with Atomic Energy Commission, Grand Junction, Colorado.

[4] Atomic Energy Commission, Denver, Colorado.

[5] Callaghan, Eugene, Volcanic sequence in the Marysvale region in southwest central Utah: Am. Geophys. Union Trans., 20th Ann. Meet., Pt. III, pp. 438–452, 1939.

men at Marysvale. Mr. Lynn Gardiner deserves credit and our thanks for much of the mineralogical work.

It should be mentioned that Messrs. H. C. Granger and H. L. Bauer, Jr. of the U. S. Geological Survey worked in this area several weeks last winter. Their official report was made available to the senior author on November 2nd. Our paper was read at the meeting of the Geological Society of America on November 16, 1950.

GENERAL GEOLOGY.

The volcanic rocks surrounding this area cover about 4,000 square miles of south central Utah. Remnants of Paleozoic and Mesozoic sediments are found in a few places. In our area some masses of quartzite of unknown age occur. They are intruded by the plutonic rocks.

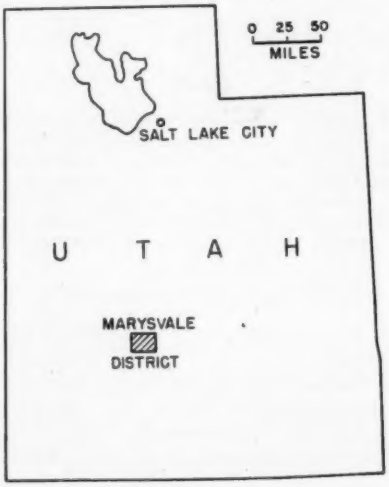
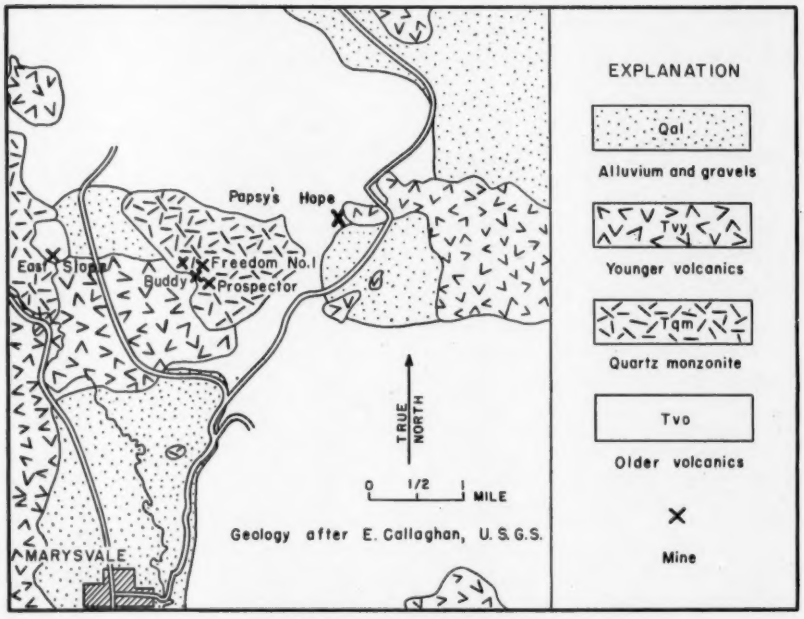


FIG. 1.

Callaghan divides the volcanics into an older series, the Bullion Canyon series, and a younger one, the Mt. Belknap series. They are separated in time by the invasions of relatively small plutonic intrusions into the older but not into the younger series. A considerable erosion interval exposed the plutonics before the younger volcanics were deposited. The older Bullion Canyon volcanics are largely alkalic and are described as latites and andesites. They form flows, tuffs and agglomerates of great thickness. The younger Mt. Belknap ones are rhyolitic. The intrusives, which are particularly important in the ore area, are latite porphyry, quartz monzonite and granite or aplite. They were grouped together by Callaghan, in his less detailed study, under quartz monzonite.

Latite Porphyry.—This rock is the oldest. It contains many phenocrysts of feldspar, mostly about ¼ inch in mean diameter although they may be twice as long as wide. They are white to cream in color, and there are probably as many plagioclase as potash feldspar grains. Biotite and pyroxene form smaller phenocrysts to a more limited extent. The groundmass is finely crystalline and is pink to purplish-gray. A few quartz phenocrysts are present. That this rock is an intrusive and not a flow is clear in the field from the following observations, though no intrusive contacts of it have been observed: (1) It is



MARYSVALE DISTRICT, UTAH

FIG. 2.

very uniform in texture; (2) it does not show flow lines, inclusions, or amygdaloidal cavities as flows do; (3) no sheeting or fracturing suggestive of flows can be observed; (4) in places it has invaded and caught up relatively large masses of sandstone, which it has metamorphosed to massive quartzite. The quartz monzonite described below has produced the same metamorphism where it is in contact with sandstone.

The latite porphyry is a very dense rock that weathers with difficulty. Talus of almost fresh-looking fragments of this porphyry covers the hills underlain by it.

Quartz Monzonite.—Most ore discoveries have been made in quartz monzonite. It has a uniformly medium-grained, granitoid texture and on fresh surface is light to medium gray. Where weathered, it assumes a dirty, greenish-yellow color. It disintegrates readily to a yellowish-green, gritty soil. The minerals in the order of abundance are soda and potash feldspars, biotite, quartz, pyroxenes, and magnetite. The biotite is conspicuous and weathers to a golden-brown color. Outcrops of this rock are commonly somewhat rounded. Spheroidal weathering is common. However, there are some quartz monzonite outcrops that form prominent crags and cliffs, although not in the immediate neighborhood of the ore deposits.

This leads one to speculate on the possibility that the ease with which this rock weathers is connected with the hydrothermal activity, which we know affected large areas in this district. In other words, depending upon the locality, we observe either hard fresh monzonite or hydrothermally altered monzonite. Another possibility is that the quartz monzonite that is soft and decomposed formed a part of the old erosion surface, which we know preceded the formation of Miocene or Pliocene agglomerates and flows described below as the Mt. Belknap series. In that case, it might have been deeply weathered previous to later burial. So far no intrusive contact has been found of this rock with an older one, except with the quartzite mentioned above and the latite porphyry. The latter has been intruded by the quartz monzonite. Where the two are in contact, neither shows any chilled border gradation. The grains are definitely interlocked, which means that the porphyry was still hot when it was intruded. Callaghan mentions that the quartz monzonite intrudes the Bullion Canyon series, but these occurrences are outside our area.

Aplite, Granite, and Granodiorite.—There occur in this area intrusive rocks that grade in texture from aplites to fine-grained granites. The writer has seen no previous mention of them, and Callaghan maps them with the quartz monzonite. Some of them are so fine in grain that they resemble a rhyolite porphyry. They are light gray to cream in color when fresh and weather to brownish and reddish-yellow. Quartz, orthoclase, and plagioclase are the conspicuous constituents, in some facies the only ones. These may grade into ones that also contain considerable amounts of biotite as essential mineral. Irregular aplite dikes from one inch to many feet in thickness cut the quartz monzonite in many places. As the aplite definitely grades into granite or granodiorite in a number of places, there can be no doubt that the granite is younger than the quartz monzonite, although it is not found in direct contact with it. The aplitic granites are dense and hard, and generally form bold conspicuous outcrops. Dikes of them occur in the ore where they are much harder than the quartz monzonite enclosing them. They are not favorable to ore deposition.

The intrusives are overlain by a series of reddish rhyolitic agglomerates and flows. These are named by Callaghan the Mt. Belknap series. They are variable in character but appear to be agglomerates where in contact with the older rocks. Higher in the series, they may display good flow banding and become very hard and resistant to erosion. The hills which are capped with this rock support few, if any, trees. The Mt. Belknap series lies on an erosion surface

of the intrusives as can be definitely proven by the following observations: (1) Cobbles and boulders of all the intrusive rocks described are incorporated in the agglomerates; (2) there is no contact action or changes in texture of the intrusive rocks at the contact with the agglomerates. Amygdaloidal cavities exist in abundance in the agglomerates and flows at or near the contact. Even pitchstone-like lenses occur very close to the contact; (3) dikes of aplite in the quartz monzonite stop at the contact with the agglomerates.

STRUCTURAL GEOLOGY.

All the structural features are tied closely to volcanic activity. As the rocks are igneous, larger faults in them, which may be present, have not been discovered. It is not possible to reconstruct the surface of the region as it existed previous to the intrusion of the plutonic rocks, but as it was a surface covered by volcanics, it probably was quite rough. Intrusions produced mountains that were eroded probably several thousand feet judging by the granitoid textures of the rocks on the old erosion surface under the flows. While this surface was still mountainous and highly uneven, the Mt. Belknap rhyolites of considerable thickness were deposited on it. For this reason, the contacts show considerable dips. Still later movements accentuated this tilting of flow and agglomerates resulting in nearly vertical contacts with the old erosion surface in places. The best examples are exposed in the open cut of the Bullion Monarch and in the incline of the Buddy Mine where dips from 30° to 70° may be observed. The present relief of this old erosion surface in the immediate area is about 500 feet, but it is probably several times this figure in the region as a whole.

The jointing of the quartz monzonite is rather prominent in places, and its mapping may show up some relationships to the ore zones, which strike N 60°–70° E in the area. Two of the better directions of jointing are N 85° W and N 35° W, but there are several others.

Of great importance are the intrusive contacts of the granitic rocks with respect to the quartz monzonite. What has been exposed of them by drilling and drifting indicates highly intricate relationships which are entirely unpredictable. As the uranium seems to prefer the quartz monzonite, the importance of these contacts is obvious. The rhyolitic flow rocks commonly have jointing which is somewhat columnar. The columns are mostly at angles of 65° to 90° to the flow banding where it was examined.

URANIUM ORE BODIES.

The primary uranium minerals, as far as we can be sure of at present, are confined largely to narrow veins and gouge-filled fissures or slips, some of them paper thin, in the quartz monzonite. It is best to speak of ore zones at present, since weathering obscures the true primary mineralization. There are also very small amounts of pitchblende as replacements in the hydrothermally altered rock proper. The extremely fine-grained nature of the pitchblende makes the recognition of individual grains in decomposed rock containing also magnetite, pyrite, jordisite (amorphous MoS_2) and ilsemannite (complex Mo sulfate) almost impossible.

The ore zones generally have a strike of N 55° to 70° E and a dip that approaches vertical. Each zone may contain one to several narrow veins or lenses of chalcedonic quartz or coarse quartz with fluorite and a little calcite. Between the veins, clay gouge and other decomposed argillic rock are common. The dark violet fluorite varies in grain size between a fraction of an inch and violet powder so fine that it looks like a pigment. There are also a few brecciated zones in which fluorite is present as drusy vugs in and surrounding fragments of the breccia.

It has been thought that the "slips" filled with gouge and showing slickensides are evidence of faulting. The movement cannot have been very extensive, however, as the slips are not continuous for any distance. The width of the zones as a whole is still unknown. Judging by the Prospector Mine workings, they swell and pinch rapidly and probably form steeply pitching ore shoots extending through the present levels of the mine. The chief concentrations of pitchblende are confined to a maximum of a few inches in any zone. Values as high as several percent of U_3O_8 have been obtained if confined to these narrow lenses.

Primary uranium minerals in this area have weathered readily to schroeckingerite, autunite, torbernite, a uranophane-like silicate, and two still unknown minerals. Schroeckingerite is probably more common in the upper 10 feet than farther down. The uranophane-like mineral is probably the most common. It is a hydrous silicate but differs from uranophane as described in the literature by its higher indices.[6] Torbernite[7] occurs sparingly.

Most of the secondary uranium mineral grains are later than goethite and grew on films or crusts of this mineral. In spite of extensive oxidation to a depth of 200 feet, very fresh looking pyrite crystals may be observed in much of the oxidized material. Some of the pyrite has a peculiar bronze color like that of cobaltite. No other sulfides have been found except the black powdery amorphous molybdenum sulfide, jordisite,[8] which occurs in a large brecciated zone in a drift in the Bullion Monarch Mine and in much less well defined zones in the Prospector Mine. This mineral would be almost impossible to identify if it did not occur with its oxidation product ilsemannite which is dark blue to black, and which with water yields acid, dark blue, solutions that may stain any other minerals in contact with them. The clay-like mineral gearksutite, $Al(F, OH)_3 \cdot CaF_2 \cdot H_2O$, and the powdery fluellite, $AlF_3 \cdot H_2O$, occur in the same brecciated zone of the Bullion Monarch Mine. The fluellite has been identified only tentatively.

Hydrothermal alteration and weathering are intimately associated in all underground and drill exposures. Sericite, as well as most of the common argillic minerals, is found completely altering the feldspars. Biotite is prob-

[6] According to determinations by Dr. Clifford Frondel, they are in Na light: Np = 1.680, Nm = 1.730, Ng = 1.77. Ours are slightly lower but variations are common. Not enough clean material has been separated for a quantitative analysis. The X-ray photographs show slight unexplained discrepancies.

[7] This torbernite is fluorescent in some specimens, and for this reason, and because no copper minerals have been observed, was mistaken for autunite at first. It is distinctly greenish in color when compared with the true autunite.

[8] The minerals jordisite, ilsemannite, gearksutite and fluellite were identified by Mr. Lynn Gardiner, University of Minnesota.

ably the only ferromagnesian mineral which has resisted hydrothermal action though not weathering. Magnetite was probably completely changed to pyrite by the hot solutions.

Uranium mineralization extends into the Mt. Belknap rhyolitic agglomerate. The contacts between them and the quartz monzonite have been prospected intensively (Fig. 3) as if ore concentration should be expected there. It is evident, however, lately substantiated by drilling, that the rising solutions did not *follow* such contacts, except accidentally, though they may have deposited much of their load where changes of rock and porosity occurred.

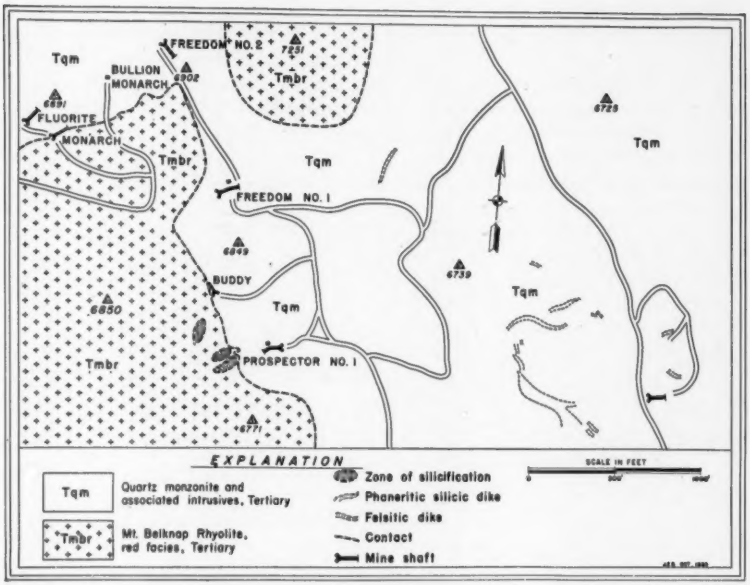


FIG. 3.

Porosity means appreciable lowering of vapor pressures for the solutions which should cause precipitation of the load. For this reason, ore should occur near the contact with the agglomerates though not very high up in them as dissipation of the solution over large porous masses would produce no merchantable ore bodies. There is, however, evidence that thorough silicification of agglomerates occurred locally on a large scale at or near this contact, for example, above the Prospector Mine. J. W. Gruner would attribute this deposition to the change in porosity. That no appreciable uranium ore occurs in the silicified rock is probably due to the tremendously large ratio of SiO_2 to U_3O_8 in the solutions.

These facts fix the age of mineralization as post-rhyolite. Some men have

been inclined to think that the occurrence of secondary uranium minerals in the younger rhyolite agglomerates might have been caused by circulating ground waters carrying the uranium upward. The best argument against this belief is that the fluorite veins and veinlets, which are always associated with the primary uranium mineralization, continue into the rhyolites for many feet. One must not conclude, however, that the converse is also true, that where fluorite occurs uranium must be present. A fluorite vein up to 2 feet thick, for example, occurs in the granite only a little distance from the Bullion Monarch ore body, yet no uranium has been found in this vein.

The Marysvale region is well known for its alunite deposits,[9] and it is natural to ask whether there is any genetic relationship between the uranium and alunite occurrences. The nearest alunite deposit, the White Horse Mine, is only about a mile from the uranium mines. It is thought by Callaghan [10] that the alunite mineralization is pre-Mt. Belknap in age as the deposits seem to be confined to the rocks of the older Bullion Canyon series. There is, of course, no good reason why the two types of deposition cannot be of different ages. It is even conceivable that not all alunite deposits are of the same age in an area of prolonged igneous activity.

MINES AND PROSPECTS.

The properties on which most of the work has been done lie in a belt that strikes about N 20° W and which is almost 2,000 feet long (Fig. 3). All workings are in quartz monzonite but may extend into granitic rock and into a few feet of overlying agglomerate. All the ore zones strike about N 55° to 70° E and appear to belong to the same fracture system. They are very similar in mineralization of the oxidized zone.

Prospector Mine.—The underground workings are in a nearly vertical ore zone striking N 65° E. Pitchblende appeared on the 70-foot level and was the first reported from the district. There are also a 136-foot and 180-foot level on which oxidation is still very considerable. At the east face of the 180-foot level a vein of fluorite, quartz, calcite and pyrite is about 15 inches wide. Pitchblende occurs in it as thin slip and gouge fillings. It is too early yet to speculate on the shape of any ore shoots, but they could be nearly vertical chimneys a few feet to 12 feet in diameter connected laterally by thin veins and slips of small tonnage. Two other veins parallel to the one described above have been discovered recently within 150 feet across the strike on this property.

Buddy Mine.—The workings were started at the contact of quartz monzonite and Mt. Belknap agglomerate. The ore is found in complicated nearly vertical fissures that appear to be connected by others which have southwestward dips varying from 10° to 50°. Pitchblende was found at a depth of 80 feet vertically. The relationship at the contact is very similar to that at the Bullion Monarch Mine described below. Some faults striking northwesterly

[9] Butler, B. S., Loughlin, G. F., Heikes, V. C., and others, The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, pp. 546–550, 1920.
Callaghan, Eugene, Preliminary report on the alunite deposits of the Marysvale region, Utah: U. S. Geol. Survey Bull. 886, pp. 130, 1938.

[10] Callaghan, Eugene, Am. Geophys. Union, op. cit., p. 446.

have been reported lately by one of the authors (I. R.). There is no way of measuring their displacements.

Bullion Monarch Mine.—The ore from this mine has come from open pits. The aggregate width of the zones in the pits is about 100 feet. Highly bleached and decomposed rhyolitic agglomerate forms most of the hanging wall on the south side. The agglomerate contact dips at angles of 30° to 70° southward. Secondary uranium minerals occur in the bleached agglomerate but have not been observed in the red facies overlying the white. Notwithstanding the steep contact, we know from drilling that it rapidly flattens toward the south to reappear 400 feet south of the open pit where quartz monzonite outcrops again. Aplitic dikes occur as irregular masses in the quartz monzonite. We know, chiefly from these exposures, that granite is not a favorable host rock for ore.

An adit 140 feet below the open pit is about 500 to 600 feet long. It did not encounter any definite ore zone in this distance as it was largely in granite. Small amounts of secondary uranium minerals are found in a few places. One of them is conspicuous for its molybdenum mineralization (jordisite). A 45° angle diamond-drill hole has penetrated a zone of probable ore approximately in the vertical extension of the southern zone exposed in the open pit. The vertical depth is about 200 feet at this point of intersection.

Freedom No. 2 Mine.—The underground workings disclose two narrow ore veins or zones 150 feet apart, which strike N 65° E. Between them numerous quartz fluorite veinlets of similar strike are found. The uranium content of the veinlets is low as a rule. All these veins are nearly vertical.

Lately the two prospects, Papsy's Hope and East Slope Claims, have attracted attention because in them mineralization occurs in the older Bullion Canyon series of volcanics. Some autunite has been found in fissures and joints of these flows or tuffs. Papsy's Hope is about 7,000 feet east, and East Slope Claim [11] is 6,000 feet west of the main ore bodies discussed.

A third locality (Sniffer Claims) occurs on the west side of the Tushar Range about ten miles west of Marysvale. It is of interest chiefly because it is reported to be in Mt. Belknap rhyolitic tuff.

CONCLUSIONS.

Uranium mineralization is widespread in the volcanics and plutonics of this region. Although quartz monzonite is the most favorable host rock found so far, prospecting has not been extensive enough in other rocks to dismiss them as unfavorable. The geologic settings of all these occurrences lead to the conclusion that the deposits are of the shallow epithermal zone and probably of late Tertiary age. They probably will not reach a greater depth than other metal deposits in similar settings, perhaps 2,000 feet, a dangerous prediction when actual mining has reached about 200 feet.

Dec. 14, 1950.

[11] When this paper was read before the Geological Society of America there was some discussion as to the presence of alunite mineralization with the uranium minerals at the East Slope Claims. Though we have tested a number of samples in the meantime, we have been unable to find alunite in the mineralized zone.

METAMORPHISM OF COAL.

A. LAHIRI.

ABSTRACT.

The metamorphism of coal in terms of pore diameter and surface area of coals of different ranks is discussed. With regard to the origin of the petrological constituents, it is pointed out that the differentiation into the banded constituents takes place at a later stage of metamorphism, and with the approach of anthracite rank there is a convergence of petrological types. Colloidal origin and polymeric constitution of the petrological constituents are considered. An attempt is made to explain the geologically observed facts in terms of physico-chemical properties of coal substance. It is concluded that metamorphism of coal can be studied best in vitrain.

INTRODUCTION.

In a recent review G. H. Cady (1)[1] has emphasized the desirability of correlating the results of chemical and physical studies on coal with the geological conditions which "by reason of their progressive increase in severity produce coal from the pre-coal material and subsequently alter coal through successive stages of increasing rank." Although he doubts whether the general concept of metamorphism can be defined in chemical or physical terms, he admits that "explanation of the process can be made only in terms of physics and chemistry employed as tools of geology." So far, we have failed to obtain a broad and generalized concept of coalification which may reconcile the seemingly contradictory geological and chemical evidences. Geologists appear to have failed to discharge their "coordinating and correlating function." In fairness it should be mentioned that the failure of the chemist has also been of equal magnitude, for nearly after half a century's work it has not yet been possible to establish unequivocally the constitution of coal. But much of the failure in obtaining a broad conception of coal metamorphism appears to have been due to the lack of appreciation of the colloidal properties of the coal substance. Time has come for a re-survey of the field. In this paper it is proposed to show that much can be learned from an examination of the colloidal structure of coal. It is even possible that the information obtained from these investigations may supply the link between the observed geological facts and the chemical properties of coal.

The potential value of research on the colloid dimension is that substances dissimilar on the chemical (molecular or atomic) plane may be similar on the colloidal, or at least they can be compared on the basis of common or simple properties. The so-called "crystallites," "micelles," or "units" of coal substance, being of the order of 100A to 1000A in size, are much too small to be studied under the microscope but are also far too big and complex to be resolved by the orthodox methods of organic chemistry.

[1] Numbers in parentheses refer to Bibliography at end of paper.

In a study of metamorphism it is customary to classify observations in three groups: (a) morphologic changes induced by metamorphism, (b) recognition of new types or facies, and the processes involved in their formation and (c) the nature of metamorphic agencies that bring about these changes.

THE ULTRA-FINE STRUCTURE OF COAL.

In a study of metamorphism of coal, little knowledge can be gained of the morphologic changes on the macroscopic or microscopic scale, except the development of banding, which is best dealt with under heading (b). However, the investigation of the *ultra-fine structure* reveals a wealth of significant information. Coals have a spongy or porous structure. These pores are of capillary dimensions but the porosity and the dimensions of the pores can be fairly measured by methods of physical chemistry. It is now established that this porous structure is in some way related to the metamorphic rank of coal and therefore has important bearing on the physico-chemical behavior of coals.

The relation between the moisture content and rank of coals has long been recognized but the significance of the moisture content in terms of the "internal surface" was not appreciated. Moisture content of coals under equilibrium conditions is a measure (although not absolute) of the porosity of coal. As the pores are of capillary dimensions (20–60 A°), the water in coal is present as a film, at the most in a layer of a few molecules thick. It exists in an adsorbed state on the "internal surface" on the pore-walls of the coal. The hysteresis phenomena observed during equilibrium moisture adsorption and desorption and other experiments indicate that this adsorbed moisture does not have the properties of bulk water but behaves as a monolayer having two dimensions only (2).

The significance of this evidence of internal surface may be illustrated by the following consideration: "a cube of 1 cm edge has a surface area of 6 cm^2 and a surface energy of 6 γ ergs, where γ is the surface tension or surface energy (in dynes/cm or ergs/cm^2) of the material composing the cube against the surrounding medium. When this cube is sub-divided into cubes of 100A° side, a size typical of many colloidal particles (*incidentally also of coal*), we now have 10^{18} cubes and, therefore, a total surface energy of 6.10^8 γ (ergs), i.e., the surface energy has been increased by a factor of a million" (3). This large surface area per unit volume (specific surface) accounts for the great adsorptive power of colloidal gel systems, which consist as a rule "of a network structure built up of anisometric particles." Thus, relatively small concentrations of a colloidal substance can hold large quantities of moisture by adsorption in the network on their internal surface. The measurement of internal surface by the heat of wetting method has shown that coals possess a surface of 20 to 200 square meters per gram, the surface generally decreasing with increasing rank of coals (4).

RELATION BETWEEN RANK AND POROSITY.

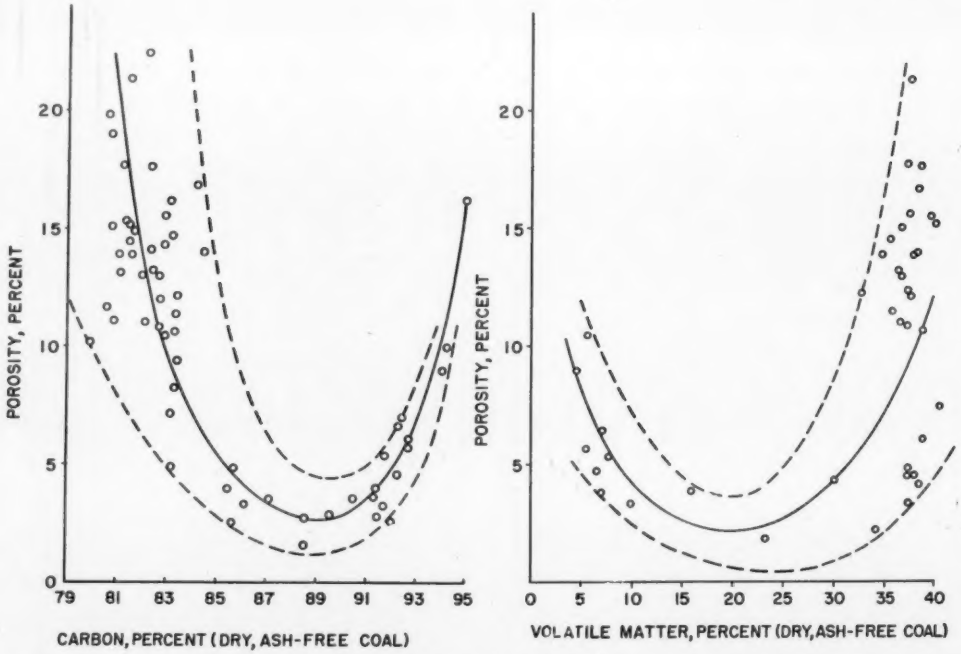
Two important investigations in which the rank of coals has been correlated to porosity or surface merit the attention of geologists. As the rank of

coal is defined by chemical criteria, it is significant that these correlation studies express the chemical properties of coal in physical terms.

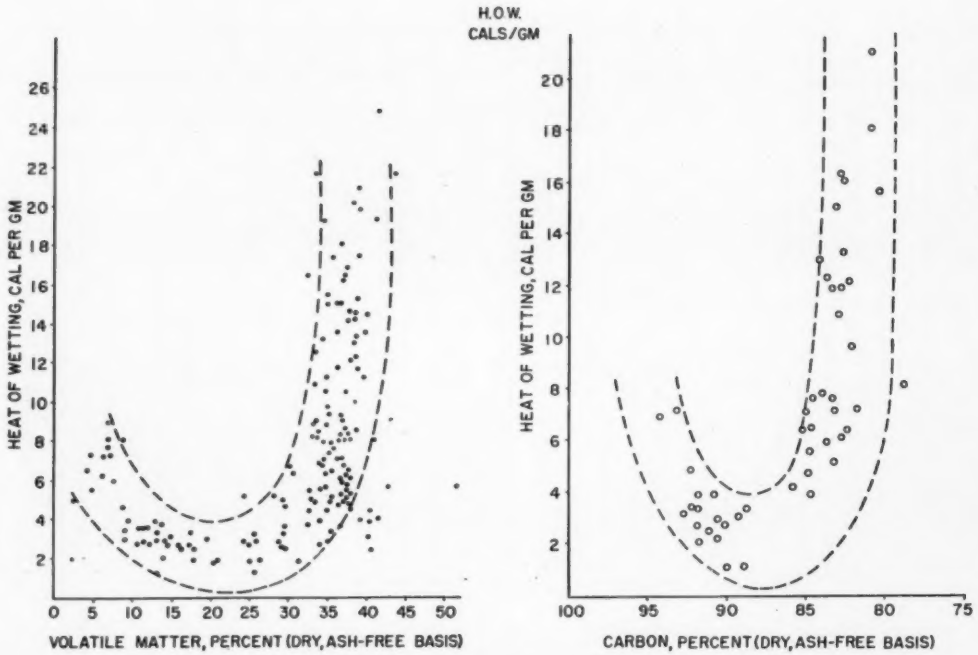
King and Wilkins (5) have correlated the rank of coals with porosity as calculated from equilibrium moisture content determinations. Figures 1 and 2 summarize their findings. Hirst and co-workers (6) determined the heat of wetting (with methanol) of coals of various ranks and their data are illustrated in Figures 3 and 4. The heat of wetting is directly proportional to the surface of coal (accessible to the molecules of methanol used for wetting). The relationship between the rank and heat of wetting of coals (Figs. 3, 4), as in the case of porosity, is, therefore, a correlation of the rank of coals with their surface areas. It will be observed that in each case the curves (or the bands) obtained form catenaries. The porosity and the surface are highest for low rank coals and decrease progressively until 89 to 90 percent carbon content is reached. Porosity and surface are then observed to increase to some extent as coals of anthracite rank are approached. This relationship has been discussed by Bangham (7) in a recent paper.

For coals ranging up to bituminous rank there can be two explanations for this relationship: (a) The size of the "micelles" or "units" of coal in higher ranks tends to increase with rank and is about ten times larger in coal of high rank (c, 1000A°) than in the coals of lowest rank (c, 20 A°). This would explain the relative higher moisture content of low rank coals, as smaller units would have greater interface. (b) Less surface is available to the measuring liquids (moisture or methanol) due to compaction and consequent constrictions in the pore diameters. In this case it is assumed that the units are of spherical shape, closely packed and "the size distribution sufficiently narrow to justify the assumption of equal size." In mature coals the pore dimensions would be constricted as a function of increasing metamorphism (dynamic?). There is no direct means of proving the validity of one assumption rather than the other, but the relation of ultrafine structure to the rank of coals is evident (Figs. 1, 2, 3, 4).

Bangham favors the second explanation cited above, and has shown that the decreasing pore diameter (26.5 to 0 A°) can be mathematically correlated with the decrease of surface and porosity. The assumption is justified by the observation that fine milling of coal for prolonged periods increases the heat of wetting of high rank coals, evidently by exposing inaccessible pores. It is considered that such milling does not produce any appreciable new surface. The advantage of this hypothesis, as Bangham has shown, is that the metamorphism of coal (rank) can be sufficiently described in terms of any one of the three parameters, viz., pore diameter, porosity, or surface area. Bangham observes, "The alternative hypothesis that the micellar size increases in the course of coalification, is less satisfactory. For, supposing the packing or degree of compaction to remain the same, the porosities of all coals should be equal; the value of d (pore constriction diameter) should, moreover, increase on passing from coals of lower to those of higher rank." But it can be stated that the packing or degree of compaction is rarely the same in any two coals. Besides, their degree of polymerization is bound to differ depending on the environmental conditions and extent of subjection to varying metamorphic influences. The de-



FIGS. 1 and 2. Variation of coal porosity with (1, left) rank of coals and (2, right) volatile matter (5).



FIGS. 3 and 4. Relation between heat of wetting and (3, left) volatile matter content and (4, right) carbon content of coals (6).

creasing average pore diameter in the face of increasing average size of the units can still be explained as due to compaction, particularly if the gel is considered to be a polydisperse system (as isogel), i.e., composed of polymeric units of different sizes. In such cases better packing of units can be obtained on compaction. The justification for assuming an isogel structure for coal has been discussed by the writer elsewhere (8) and need not be repeated here. Indeed the modern concept of polymeric constitution of coal involves the assumption of increasing degree of polymerization (therefore, also in size of units) with increase of rank, as otherwise the loss of volatile matter and enrichment in carbon could not be explained.

Geologically coal is known to be a mixture of the recognizable petrographical constituents. Bangham admits that his observations are chiefly confined to the bright coals and they have "no real application to durain (or hards) per se." Experiments have shown (9) that durains are marked by higher porosity, and X-ray shadowgraphs (10) "showed the existence of pore structure altogether too coarse to be accounted for on the basis of interspaces between closely packed micelles." Attention may also be called to the important work of Rees et al. (11) who determined the porosity and distribution of pore sizes of the various petrographical constituents of a coal: "In fusain the largest amount of moisture is held in large pores of the size range 9.80–30.60 $\times$ 10^{-7} cm. Durain, clarain and vitrain have the largest amount of moisture in the pores of size ranges 0.65–1.35 $\times$ 10^{-7} cm. More than 90 per cent of the total amount of moisture held by fusain at 96.7 per cent relative humidity is held in pores of the size range 1.35–1.99 $\times$ 10^{-7} cm. and larger, the durain having 45 per cent of the moisture in this range and vitrain about 30 per cent." These observations not only show that the petrographical constituents differ in moisture adsorption capacity (the significance of which will be considered later) but there is also a characteristic distribution of pore size within each constituent.

The criterion of *average* pore diameter as a measure of geometry of packing, therefore, appears to be an over-simplification, however convenient it may be for mathematical purposes. That finally porosity increases in high rank coals is also evident from the catenary shape of the porosity-rank curves. Evidently in anthracite, coal has reached a stage where the converging degree of polymerization of the whole of the coal substance produces an assemblage of uniformly larger sized units and shows a recrudescence of surface (or porosity) in spite of higher compaction.

It therefore appears that compaction and partial increase in size of polymeric units are simultaneous processes, and in the lower rank (bituminous) coals the effect of the increasing size of the units is offset by the plastic yield of the smaller and dispersed mobile polymers. Whichever may be the true explanation of the phenomena observed, it is clearly of significance to the geologist. Since a morphological change describes sufficiently the metamorphic grade of coal, studies on geologic (tectonic?) compression of the coalified strata and its effect on equilibrium moisture content, porosity, and distribution of pore size should be of great importance. A mineralogic study of the associated rocks may also help in establishing the order of metamorphism in coal as in the case of the classic work in the South Wales coalfield in the United Kingdom.

DEVELOPMENT OF BANDED STRUCTURE.

The effect of metamorphism in production of new types of coal may now be considered. Schopf (12) has pointed out that the coalification is due to two overlapping, but nevertheless distinctly separate processes. In the diagenetic phase, during peat accumulation, biochemical and chemical activities predominate and it can be assumed that the environmental conditions in this stage may be a decisive factor in the direction of changes that will be operative in the future. For example, it is possible that the conditions at this stage may well dictate whether bituminization or oil-formation will take place. There is little information about the changes that take place in this period, but the work of Mackenzie-Taylor (13) on the influences of aerobic and anaerobic bacterial decomposition in the production of bitumen and oil is of interest.

With consolidation of the peat the diagenetic influences are replaced by metamorphic effects, chiefly earth pressure. There is at this stage a swollen gel entrapping large quantities of water in its network. Since the diagenetic activities are not uniform throughout the mass and the products are derived from a collection of heterogeneous plant material, it is reasonable to consider the gel as a polydisperse system. During the next stage, i.e., ageing of the gel, dehydration takes place under continued metamorphic influence. At the same time slow polymerization of the units takes place. Evidently at this stage the polymers of varying size and molecular weight would be produced due to the heterogeneity of the starting material and their unequal response to the polymerization process, although, as it will be shown later, with time there is a tendency of convergence towards a uniform size in the highest metamorphic grades. The main observed effects of these changes are compaction and vitrinization (or more correctly bituminization).

Vitrinization has been described by Schopf (12) as a "generalized process embracing considerable diversity" and since the greater part of the coal consists of vitrinized material, the general concept of coalification applies most directly to it. "It seems therefore, except for terminological qualification with reference to the lowest rank coal, that the related petrographic terminology and the vitrinization concept in particular are appropriate and applicable to all stages of coal formation . . . all types of cellular tissues and some kinds of indigenous plant inclusions and secretions may appear in vitrinized preservation in coal. Colloidally dispersed humic matter, when present, doubtless is effected by the same process" (Schopf). The belief that "vitrinization seems chiefly to involve a certain trend of chemical modification and transmutation of cell wall substances," no doubt comes from the often observed cell wall structures in vitrain.

The concept of bituminization cannot, however, be confined to any one type of plant material. Cady (14), Dapples (15), Marshall (16) and others now believe that vitrain is the predominant constituent in coal. Most coal petrographers (Cady, Schopf) agree that the changing physical appearance of coal is due to the relative proportions of vitrain, and that leaving aside the "phyterals," coal can be considered primarily as mixture of vitrain and fusain. The other macroscopic types are then regarded primarily as material having varying con-

centrations of vitrain and fusain. This realistic approach can be considered as a true advance in coal petrography.

The banded structure is not, however, observed in low rank coals, say lignites. But eminent coal petrographers (Schopf, Seyler) do not hesitate to recognize the groundmass of lignites as vitrain, although strictly the macroscopic characteristics of vitrain, e.g., luster and fracture, are not developed in lignites. Microscopically the groundmass of lignites has all the characteristics of anthraxylon. Recognition of this fact is also of basic importance. It means that in the lignite stage, the coal substance exists in an undifferentiated state, predominantly composed of vitrain (with minor amount of fusain). It follows, therefore, that the development of banded structure is a post-depositional metamorphic feature and is not due to original difference in plant constituents as assumed by botanists. Before attempting to find an explanation of the origin or mechanism of development of banded structure it is necessary to consider in detail the physical and chemical nature of the banded constituents.

Lowry (17) has remarked "No exact chemical correlation has been made, and may never be made, between the chemistry and petrography of coal. . . . When such objects, different as they may appear optically, are subjected to the drastic chemical degradation reactions necessary for precise chemical definition, the apparent differences may not be . . . and are not found." This statement is in complete support of the colloidal polymeric concept of coal constitution. Nevertheless, careful sampling and analysis of bright and dull constituents show some persistent difference in composition and chemical reactivity. Bright coals have, on the average, lower carbon, higher hydrogen, nitrogen, and sulfur content than dull coals and fusain. The dull coals have lower carbon and higher hydrogen, nitrogen, and sulfur than fusain and are intermediate between vitrain and fusain. The analyses of dull coals drift either way considerably, showing that they are essentially mixtures. But the constituents themselves, bright or dull, may vary considerably and show all gradations, however carefully they may be chosen. The work of Wandless and Macrae (18) and Berry and Jones (19) on gravity separation of the constituents and the analysis of the products separated prove this beyond doubt. Such gradations between the constituents and within them are only conceivable if we accept the idea that coal substance is a polydisperse polymeric system, idealized as isogel. The differences in composition can then be attributed to concentration of polymeric units having undergone varying degrees of polymerization. The progressive nature of the variation in chemical composition is also in accordance with the nature of polydisperse colloids. With increase in metamorphism it would be expected that there would be a tendency to attain a uniform degree of polymerization, or, in geological terms, there will be a convergence. This is also what is found in coal. Analytical data suggest (17) that differences in elementary composition of the petrographic constituents decrease with increasing rank. With increasing carbon content the hydrogen content of bright coals declines and becomes indistinguishable from the hydrogen content of other associated types. There is a similar convergence of other chemical properties. Microscopic evidences also point to a similar conclusion (12). But even more significant from the point of view of difference in polymer size are the data on equilibrium moisture con-

tent of Rees et al. (11). The decreasing adsorptive power of the petrographical constituents in the order of vitrain, clarain, durain and fusain confirms the increasing order of size of the polymeric units and the hydrophylic nature of the smaller and simpler constituents in vitrain. It is conceivable that under the circumstances of origin there will be little clear-cut differentiation and all gradations should exist. In anthracite all components approach the chemical composition of fusain.

The ash content generally increases in order of bright coal, dull coal, and fusain, but the bright coal or vitrain is commonly notably pure, whether in thick bands or in microbands. Not only is there a difference in quantity but there is also a difference between the chemical nature of the mineral matter in bright and dull coals. The particle size of mineral matter in vitrain is also much smaller than in associated dull components. These observations are much more striking in the banded constituents of coals of drift origin as found in India. It is inconceivable that this persistent difference, even in the thinnest of microbands in a seam of 100 feet or so thick, can be a depositional or preconsolidation feature. It is generally assumed that the ash in vitrain is derived from the original plant constituents and therefore differs in composition from the co-deposited mineral matter. But in lignites, the vitrain permeates the whole of the coal substance, whereas in mature coals they appear as bands. In fact, with many banded coals of India it is found that the process of coal cleaning by gravity separation method is primarily a petrographical separation. This difference in mineral matter content cannot be explained unless banding in coals is assumed to be a post-depositional feature. If this is true we may ask, how the banding develops with progress of metamorphism and also how it is destroyed in the highest ranks. A possible answer may be found if one considers the colloidal properties of gel assuming that it is a poly-disperse system to start with.

The relative hydrophylic nature of vitrain has already been pointed out. Vitrain invariably has a higher moisture content than the associated constituents. Geological occurrence of transportation of vitrain in colloidal dispersion in water is also known. Fermor (20) has recorded occurrence of veins of vitrain across the bedding plane of rocks in Malaya. The high affinity for moisture of vitrain is due to the smaller sizes of the constituent polymeric units which have higher interface. Consequently, these constituents are more mobile. The larger and more complex polymeric units are less mobile. Due to their lower moisture content and therefore lower degree of dispersion there will also be a greater tendency of coagulation amongst these constituents. With increasing time of compaction and loss of moisture the degree of coagulation (or, more strictly, coacervation) increases. No doubt colloidal electrolytes present in the form of inorganic ions also influence this coagulation process. With increasing flocculation the gel will undergo synaeresis by forming a higher particle density and expelling the corresponding amount of fluid. The more mobile and hydrophylic constituents like vitrain would now tend to be squeezed out of the coagulate. Due to the restricted mobility complete differentiation cannot take place and the process, therefore, gives rise to banding. Thicker

bands would be developed where mobility and concentration favors the diffusion process.

This segregation process may become more marked due to the presence of inorganic gels which may act as a diffusion barrier. The alumino-silicic acid gels will allow diffusion of the smaller and mobile constituents but prevent the movement of the larger molecular aggregates. The inorganic gels may also exert selective adsorption influence and adsorb the larger units on their surface. Thus when the gel is finally dehydrated and compacted, the segregated bands would become macroscopically distinct and also have different chemical composition and ash content. It is to be expected that there will be all degrees of segregation resulting in mixtures and gradations of all kinds as is, in fact, found in the petrographical constituents of coal. This conception of origin of the banded constituents would also explain the differences (as well as similarities) in their chemical behavior.

Summarizing the review of chemical properties of banded constituents Lowry (17) has stated "Extensive studies have been made to find fundamental difference in chemical structures of the associated petrographic constituents without success. There appears to be a gradation of properties from one component to the next, but there is no indication of the presence of essentially distinct types of chemical compounds peculiar to any of the ingredients of banded coals. In general, chemical reactivity decreases from the bright component to the dull to fusain; this is in accord with general difference in chemical analysis, since chemical reactivity also usually decreases with increasing rank of coal." These observations appear to be logically explained by the theory of origin of the banded structure presented here. The differences in chemical behavior, e.g., effect of solvents, hydrogenation, oxidation and thermal decomposition on the various banded constituents, can also be understood.

FUSAIN.

Schopf (12) considers fusain (or the fusinization process) to be of diagenetic origin. Fusinization appears to be the most rapid and extreme change from the original plant material. Many workers believe that plant tissues are fusinized before accumulation of overburden. Sprunk (21) has stated that "the organic matter in course of decomposition by biological agencies undergoes chemical changes that are in some respects similar to those of metamorphic processes such as pressure and heat. Apparently the opaque matter has undergone devolatilization in the peat stage through loss of hydrogen, oxygen, sulphur and nitrogen, and there was abundant enrichment of carbon as decay progressed, although some carbon was undoubtedly lost as carbon dioxide and methane." On the other hand, the similarity in chemical composition, the recognition of semifusain (where all gradations between fusain and vitrain are observed) and the tendency of vitrain to converge to fusain-like composition and opacity in higher ranks indicate that there is no fundamental difference in chemical constitution between fusain and vitrain. The same types of plant constituents that are considered liable to be fusinized are also found vitrinized. Further, biological decay, if unrestricted, seldom leads to abundant enrichment

of carbon. It is known, however, that asphaltic products can be easily converted to highly polymerized states (carbenes or carboids) by rapid oxidation, particularly in the presence of catalysts. The association of mineral matter with fusain (which is often found to fill the cell cavities of fusinized tissues) appears to suggest that inorganic constituents may be a factor in fusinization. The fact that some clay minerals in colloidal state under certain conditions (e.g., on crushing) are capable of liberating atomic oxygen may be of significance.[2] Oxidation of bitumen up to a certain stage does not necessarily involve addition of oxygen to the molecule, particularly if the substance undergoes further polymerization and the chief effect is a dehydrogenation. However, further studies are required before the mode of origin of fusain can be definitely established.

PHYTERALS.

The term *phyteral* has been coined (1, 14) to designate the plant forms and fossils in coal as distingushed from the organic coal substance. It is purely a morphological term and does not signify chemical property. The literature on coal petrography is full of confused and ill-defined terms. Megascopic, microscopic, botanical and quasi-mineralogical terms have been superimposed on each other until the subject has been reduced to a nightmare of definitions. The clear cut distinction made by Cady in coining the term "phyteral" is, therefore, welcome. Phyterals include pollen and spore coats, plant cuticles, algal remains, fossil resins and other botanical entities and their impressions seen in coal under the microscope.

In thin sections some of the phyterals are observed in striking contrast to the rest of the groundmass due to their exceptional translucency and yellow color. This feature has led to the conception that the phyterals represent original plant material and are relics in coals of high ranks. Some have therefore attempted to give them a mineralogical significance in the coal rock. Such ideas have been strengthened by the difference in chemical composition of phyterals and the groundmass of coal. For example, Fisher et al. (22) have shown that spore coats of some modern plant and fossil phyterals from coal yield similar products on hydrogenation and differ from the basic coal substance in their greater yield of saturated hydrocarbons. Such differences in chemical composition as observed (e.g., in their hydrogen content) are, however, no more than can be found in a polymeric group, varying in their extent of polymerization.

Schopf (12) has shown that the characteristic translucency of phyterals gradually disappears with increase of rank of coals. Low volatile and semianthracitic coals do not show any yellow coloration even in the thinnest sections although morphologically they are comparable to the phyterals in sub-bituminous or high volatile coals. In such cases the petrographer is at a loss whether to classify the phyterals separately or along with vitrain. In anthracites the composition of the phyterals is the same as the rest of the groundmass of coal, although botanical characteristics can still be recognized (23). Schopf has recorded (12) that in South African coals affected by igneous sills, the phyteral

[2] Hauser, Symp. on Colloids, Amer. Chem. Soc., St. Louis, June, 1950.

color appears to change in the same way towards increasing heat as in the case of coals of increasing metamorphic rank. The major changes appear to take place in the region of 23 to 25 percent volatile matter content of coals. These observations point toward the fundamental similarity in chemical composition between the organic composition of the phyterals and of the coal substance, particularly of vitrain. In the high rank coals, therefore, it may be accepted that the phyterals are fossilized and not "relics," in spite of the morphology. The phenomenon is similar, say, to silicification of wood. In thin sections, fossil wood will show all the botanical details of living plants but chemically it is composed chiefly of silica. However, the exceptional translucency and the low order of polymerization of the organic material of the phyterals in low rank coals require explanation.

A possible explanation may be found in the difference in permeability of the various types of plant tissues. The cell walls of the woody portions appear to be permeable to vitrain-type of bitumen but not to fusain. Fusinized portions always show empty cell cavities or the cavities are filled with minerals which might have infiltered in colloidal solution through the relatively large pores of fusain. Similarly, it can be expected that the lowest order of polymers in coals would diffuse through the fine membranes of spore coats which are not permeable to larger molecules. Thus, a further differentiation in the polymeric constituents would result from the physical properties of the original material. The high translucency, the difference in chemical composition, as well as the subsequent convergence of phyteral chemicals towards a uniform composition can then be understood. The fine structure of the spore membrane would also appear to explain the relative resistivity to chemical attack. Apparently the differentiation takes place early in the history of coal formation, before polymerization is sufficiently advanced.

CLARAIN AND DURAIN.

Clarain and durain are considered to be attrital. The former is characterized by association of phyterals, the latter by opaque matter (micrinite). Vitrain (or microvitrain) occurs in both in varied proportions either as bands or in dispersed form in the groundmass. Clearly the mixture varies widely in composition and to recognize these as "primary coals" or fundamentally different petrographical constituents is impossible. For descriptive and empirical purposes the terms may be retained with due reservations in mind. A realistic approach to a definition of these constituents macroscopically in terms of limits of thickness of vitrain as proposed by Cady (14) and Parks (24) is, therefore, welcome.

With refinement of technique and due understanding of the nature of the banded constituents, petrographic analysis may possibly become as useful as proximate analysis of coals. However, no empirical data are useful unless they are correlated to the industrial behavior of the coal.

Careful consideration of the geological and chemical evidences and their interpretation from the colloid viewpoint, therefore, indicate that coal is essentially a "monomineral" rock. The coal "mineral" may vary in size and com-

plexity of composition and structure in the same sample but fundamentally there is little difference except in its colloidal properties.

It has already been indicated that the metamorphic agency involved appears to be pressure, possibly shearing pressure.

Under normal metamorphic conditions the end product of metamorphism of coal does not seem to be graphite as many suppose. Microscopic and chemical evidences suggest that the maximum degree of polymerization and uniformity (convergence) is reached in anthracites. This is also supported by the relation of true density of coals with their hydrogen content. It has been shown (25) that the true densities determined by helium displacement of coals (as well as of the petrographical constituents) have a linear relation to their hydrogen content. This relationship shows that a coal of zero hydrogen content (approaching chemical composition of graphite) will have a density of 1.85 which is much lower than the density of graphite. It, therefore, appears that heat does not play any significant part in metamorphism of coal. This is also supported by the observed effects of intrusions in coal seams. In such cases coal undergoes carbonization and the effect has no parallel in the metamorphic grades of coal.

Breger (26) has shown that demethoxylation of lignin can be effected by shearing stress. His views can be supported by many geological evidences. The Jammu (Kashmir, India) lignites of Tertiary age are found to have been metamorphosed to semi-anthracites by tectonic pressures. The fact that coking coals have low internal surface and are often associated with tectonically disturbed rocks is also of significance (8). In the preceding pages the relation between rank and compaction of coal has also been described.

The concept of the iso-colloid nature of coal and correlation of the effect of metamorphism with the extent of polymerization introduce a difficulty in the study of metamorphism of coal. It implies that material of different order of metamorphism can exist in the same coal sample and, as such, it has no parallel with the metamorphism of inorganic rocks. In order to evaluate the effect of metamorphism, therefore, it is justifiable to deal with one constituent of the coal only, viz., vitrain, where the effect of metamorphism can be best observed and followed. Schopf (12) has observed that with increase in rank vitrain loses moisture (signifying increase in the size of micelles) and volatile matter (indicating increased polymerization) and gains in carbon content. It becomes optically denser, indicating increase in refractive index, also a result of increasing polymerization. At the same time its chemical reactivity decreases. Sprunk (21) has stated that there is a linear relation between the carbon and oxygen contents of anthraxylon obtained from fossil fuels ranging in rank from peat to anthracite. Marshall (16) observes, "When carbon, oxygen and hydrogen contents of vitrinites from coals of all ages and rank are graphed, there is obtained a curve similar to the 'coal belt' of Hickling. It is much more restricted in width, corresponding to a smaller variation in the content of hydrogen. The linear nature of carbon/oxygen relationship is very striking."

For study of the rank of vitrain it is desirable that the purely qualitative criterion of optical density of the samples in thin sections should be replaced by

a quantitative physical criterion. Such a property is refractive index. McCabe (27) has shown that rank of vitrain can be correlated with its refractive index. Recently K. C. Lahiri (28) has confirmed this observation. In a preliminary study of Indian coals he showed that the refractive index of vitrains from coals from the same coal field had a linear relation to their carbon content. The technique of determination of refractive index (by measuring the angle of polarization of light reflected from the surface of vitrain), however, requires further refinement for more accurate determinations. In the latest development in the field of coal petrography, Seyler (29) has used the property of reflectance (over extremely small surfaces of coal) as a quantitative measure of metamorphic upgrading of coal. It may be noted that Seyler deals with the coal substance in terms of vitrinite only. According to him, the highest form of vitrinite has the same order of reflectance power as fusinite, which is in accordance with the concept of coal metamorphism outlined here. It should be remembered that reflectance and refraction are allied optical properties and are, therefore, measures of the same fundamental changes in coal. Seyler's observation of orderly but discontinuous change of this property is, however, a matter for further study. It is not impossible that statistically the degrees of polymerization of coal substance resolve into nine or more discrete orders or it may also be that the fact observed by him is a characteristic of the instrument used.

It is not claimed that the concepts introduced here are true or experimentally established, but they appear to be probable in the light of present knowledge of chemical and colloidal properties of the coal substance. An attempt has been made to explain the geologically observed facts in terms of the physico-chemical properties of coal. Only future work can show whether the concepts are valid.

SUMMARY.

Coal is considered as a polydispersed polymeric colloidal system. It is envisaged that the degree of polymerization is enhanced by continued earth pressures. The compaction of the coal-gel leads to dehydration, which is followed by synaeresis of the gel, the larger and complex polymeric units coagulate, expelling the smaller and mobile units, thus giving rise to the banded structure in coals. This process is further diversified by the presence of inorganic gels which may act as a diffusion barrier. The metamorphism of coal can be studied in terms of physical parameters, porosity, or surface. The metamorphic changes can be best followed by a study of the physical and chemical properties of vitrain. Optically, the refraction index of vitrain appears to be a reliable guide to its rank.

Grateful acknowledgment is made to Dr. G. H. Cady, Illinois Geological Survey, for his interest and help in the publication of this paper. This paper was written during the writer's stay at Massachusetts Institute of Technology on the Foreign Students Summer Project, 1950.

NATIONAL FUEL RESEARCH LABORATORY,
JEALGORA, MANBHAM,
BIHAR, INDIA,
Nov. 1, 1950.

BIBLIOGRAPHY.

1. Cady, G. H., Coal geology: an opportunity for research and study: Econ. Geol., vol. 44, no. 1, pp. 1–12, 1949.
2. Bond, R. L., et al., Water in coal: Fuel, vol. 29, no. 4, pp. 83–93, April 1950.
3. Alexander, A. E., and Johnson, P., Colloid Science, vol. 1, p. 34, Clarendon Press, Oxford, 1949.
4. Maggs, F. A. P., The relation between heat of wetting and the absolute value of the surface area of coals: Inst. of Fuel Jour., vol. 17, pp. 49–54, December 1943.
5. King, J. G., and Wilkins, E. T., The internal structure of coal: Conference on Ultra-fine Structure of Coals and Cokes Proc., B.C.U.R.A., pp. 46–56, London, 1944.
6. Griffith, M., and Hirst, W., The heat of wetting of coals in organic liquids: Conference on Ultra-fine Structure of Coals and Cokes Proc., B.C.U.R.A., pp. 80–94, London, 1944.
7. Bangham, D. H., et al., A structural model for coal substance: Fuel, vol. 28, no. 10, pp. 231–237, October 1949.
8. Lahiri, A., Colloidal structure of coal and mechanism of coke formation, Unpublished manuscript.
9. Report of the Fuel Research Board for the year ended 31st March, 1938, His Majesty's Stationery Office, London.
10. Beeching, R., Radiographic examination of coal: Inst. of Fuel Jour., vol. 12, pp. 35–39, October 1938.
11. Rees, O. W., Land, G. W., and Reed, F. H., Moisture relations of banded ingredients in an Illinois coal: Ind. and Eng. Chemistry, vol. 33, pp. 416–419, March 1941.
12. Schopf, J. M., Variable coalification—processes involved in coal formation: Econ. Geol., vol. 43, no. 3, pp. 207–225, May 1948.
13. Taylor, E. M., Base exchange and its bearing on the origin of coal: Fuel, vol. 5, no. 5, pp. 195–202, May 1926.

——, The decomposition of vegetable matter under soils containing calcium and sodium as replaceable bases: Fuel, vol. 6, no. 8, pp. 359–367, August 1927.

——, The replaceable bases in the roofs of bituminous coal seams of Cretaceous age: Fuel, vol. 7, no. 3, pp. 127–128, March 1928.

——, The replaceable bases in roofs of bituminous coal seams of Tertiary age: Fuel, vol. 7, no. 3, pp. 129–130, March 1928.

14. Cady, G. H., Modern concepts of the physical constitution of coal: Jour. Geology, vol. 50, no. 4, pp. 337–357, 1942.
15. Dapples, E. C., Physical constitution of coal as related to coal description and classification: Jour. Geology, vol. 50, no. 4, pp. 437–450, 1942.
16. Marshall, C. E., Modern conceptions of the physical constitution of coal and related research in Britain: Jour. Geology, vol. 50, no. 4, pp. 385–405, 1942.
17. Lowry, H. H., Relation of the physical constitution of coal to its chemical characteristics: Jour. Geology, vol. 50, no. 4, pp. 357–384, 1942.
18. Wandless, A. M., and Macrae, J. C., The banded constituents of coal: Fuel, vol. 13, no. 1, pp. 4–15, January 1934.
19. Berry, H., and Jones, J. H., Physical and chemical survey of the national coal reserves: the fractional gravity separation of the banded constituents of coal: Fuel, vol. 15, no. 12, pp. 343–351, December 1936.
20. Fermor, L. L., Discussion in Proc. of a Conference on the Ultra-fine Structure of Coals and Coke, B.C.U.R.A., p. 167, London, 1944.
21. Sprunk, G. C., Influence of physical constitution of coal upon its chemical, hydrogenation, and carbonization properties: Jour. Geology, vol. 50, no. 4, pp. 411–436, 1942.
22. Fisher, C. H., et al., Hydrogenation of cannel coals and their petrographic constituents: Fuel, vol. 19, no. 4, pp. 84–88, May 1940; Fuel, vol. 19, no. 5, pp. 110–118, June 1940.
23. Turner, H. G., Microscopial structure of anthracite: Am. Inst. Min. Met. Eng. Trans., vol. 71, pp. 127–148, 1925.
24. Parks, B. C., Petrographic analysis of coal by the particle count method: Econ. Geol., vol. 44, no. 5, pp. 376–424, August 1949.
25. Franklin, R. E., A note on true density, chemical composition, and structure of coals and carbonized coals: Fuel, vol. 27, no. 2, pp. 46–49, 1948.
26. Breger, I., Geochemical investigations of coal: Conf. on Origin and Constitution of Coal, Nova Scotia, June 1950, unpublished.
27. McCabe, L. C., Some physical evidences of development of rank in vitrain: Fuel, vol. 16, no. 10, pp. 309–316, October 1937.
28. Lahiri, K. C., Indian Science Congress Proc., 1950.
29. Seyler, C. A., and Edwards, W. J., Technique of coal petrography: Fuel, vol. 28, no. 6, pp. 121–126, June 1949.

THE OCCURRENCE OF GOLD AT THE GETCHELL MINE, NEVADA.[1]

PETER JORALEMON.

ABSTRACT.

The Getchell veins are lenticular replacement bodies lying along arcuate branches of a complex range-front fault system. The fault zone cuts all rocks of the district and is tentatively dated as late Tertiary.

The more intensely mineralized portions of the deposit form a shallow blanket with roots that project downward into areas of sparse mineralization. The gold shoots are restricted to areas of intense mineralization.

Native gold and native silver are the only economic minerals. The great bulk of the gold occurs in minute but microscopically visible particles. Some gold may also occur in submicroscopic particles and some may be in solid solution in pyrite and carbon.

The ore minerals, dissolved in alkali sulfide solutions, are believed to have been deposited when the sulfide ion concentration in the hydrothermal liquid decreased, making unstable the double sulfides of gold, iron, and arsenic.

The Getchell deposit is similar in many ways to the Nevada quicksilver deposits and present-day hot-spring deposits. The Getchell ore occurrence may represent a gradation from the common epithermal gold deposit to the cinnabar deposit. It is therefore placed close to the feeblest end of the epithermal group.

INTRODUCTION.

In the past, a number of important gold mines have produced millions of dollars in gold from ore in which no gold could be seen. The Getchell gold deposit is the most recently discovered of these mines of "invisible" gold. Because gold had not been seen in the ore, either at Getchell or at similar deposits, the problem of the state, or occurrence, of the gold has been subject to considerable controversy. A prime purpose of the present study has been to ascertain whether the modern microscopic and polished-section techniques are capable of shedding some light on the problems of gold occurrence.

Location and History.—The Getchell mine is located in the northeastern corner of the Osgood Range in east-central Humboldt County, Nevada (Fig. 1). It lies 26 miles north of the town of Golconda and some 15 miles northwest of Red House, the nearest railroad station.

The gold deposit is in the old Potosi mining district but was itself not discovered until 1934. Between 1934 and 1945, the deposit was extensively explored by both surface and underground workings. A 1,000-ton mill was erected, and in 1944 and 1945, the Getchell mine had become the largest gold producer in Nevada. In 1945, mining had nearly exhausted the oxidized ore and it became apparent that milling practices in use were not suitable for

[1] Undertaken in part as a Samuel Franklin Emmons Memorial Fellowship award.

treating the sulfide ore. Mining operations were halted and an intensive metallurgical research program was begun. In 1947, a pilot mill was started treating 100 tons a day. By the summer of 1948 a satisfactory flow sheet had been developed and construction began on a 1,500-ton mill. Production, at present limited to 1,000 tons a day, will be increased upon the completion of the mill.

Acknowledgments.—The writer is indebted to the staff of the Getchell mine, and particularly to Mr. R. A. Hardy, for financial assistance and wholehearted cooperation. G. S. Koch and R. S. Creely ably assisted in the two summers of field work.

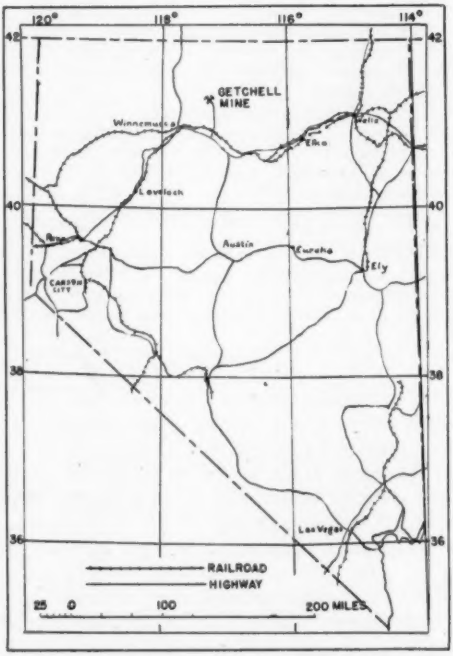


FIG. 1. Index map of Nevada showing location of Getchell mine.

The laboratory portion of this study has been carried on with the aid of a Samuel Franklin Emmons Memorial Fellowship.

The faculty of the Department of Geology at Harvard University has made valuable criticism and given much assistance in the laboratory work. Professor L. C. Graton in particular has donated generously of his time and experience. All polished sections were prepared by Mr. Charles Fletcher at the Harvard Laboratory of Mining Geology.

GENERAL GEOLOGY.

The Osgood Range is apparently a typical Great Basin Range. Its steep flanks are topped by rolling uplands in the center of the range and it is bounded on at least one side by normal faults that are responsible for the uplift of the range.

The mountains are composed of sediments of Paleozoic age that have been cut by a series of faults into isolated structural blocks (16).[2] The attitude of the rocks varies widely from block to block. The sediments are intruded by a large stock of Mesozoic granodiorite and a series of related dacite porphyry dikes, and by small Tertiary andesite porphyry dikes. Basalt flows and a small body of rhyolite tuff are products of Tertiary volcanism. Irregular patches of the tuff near the mine have been silicified and closely resemble the opalite found in certain Nevada quicksilver deposits (3).

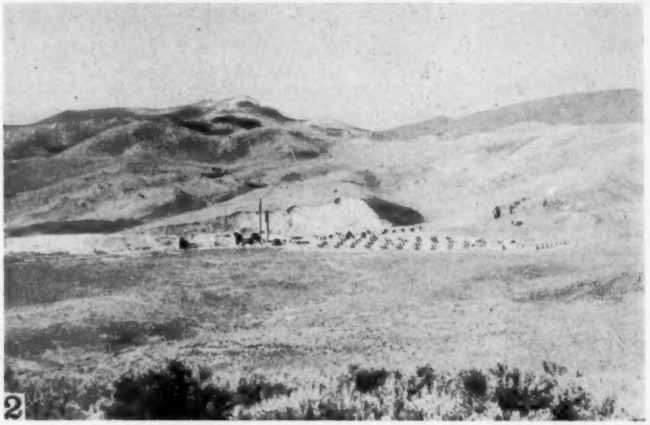


FIG. 2. Getchell Mine, Nevada. The scars on the hill behind the camp mark the footwalls of the open pits.

Descriptive Geology of the Getchell Mine.—The bedded rocks of the mine area are interbedded limestone and carbonaceous argillite (Fig. 5). The most striking feature of the sediments is the extreme lenticularity of the limestone beds, as shown in Figure 3. Limestone formations several hundred feet thick may drastically thin or pinch out completely in a strike length of less than 1,000 feet.

The sediments are intruded by the large granodiorite stock, the northeastern lobe of which is cut off by the fault zone along which the gold ore bodies occur. Later andesite porphyry dikes, trending more or less northerly, are apparently localized in and near this fault zone. A roughly conical pipe of altered rhyolite porphyry tuff lies to the east of this fault.

[2] Numbers in parentheses refer to Bibliography at end of paper.

Structure.—The principal structure of the sediments is a fold whose axis plunges at about 45° northeast. Along the southern limb of the fold, the sediments strike northerly and dip moderately to the east, and to the north they are isoclinally folded and dip to the northeast. This structure has been important in localizing the Getchell ore bodies.

The Getchell fault zone is the dominant structural feature of the mine area. It trends in a northerly direction and is composed of a persistent, footwall strand dipping moderately to the east, with steeper, arcuate hanging-wall branches (Figs. 3, 4). The footwall strand is shown by well-developed mullion and drag-fold structures to be a rift fault, along which the hanging-wall block moved an unknown distance with respect to the footwall block (Fig. 6). Later normal movement, indicated by steeply pitching slickensides engraved on the mullion faces, took place along this footwall strand. The steeper, hanging-wall branches were formed at that time and occur above flexures in the footwall fault where the dip flattens, as shown in Figure 4.

ORE DEPOSITS.

General Features.—The gold ore bodies are sheet-like masses that lie along the various strands of the Getchell fault zone. They extend at least 7,000 feet horizontally and 800 feet down the dip, and vary in width from a few feet to more than 200, averaging about 40 feet wide. The vein pattern, extremely complex at the surface, becomes simpler with depth and, deeper than 800 feet below the surface, all the branch veins apparently join to form a single persistent structure, illustrated in Figure 4.

Gangue Minerals.—The veins consist of sheared and mineralized argillite and limestone cut by quartz and calcite veins and containing a soft, plastic gumbo that has replaced the sediments. The gumbo is the principal gold-bearer. Barite, gypsum, fluorite, and chabazite are minor gangue minerals and occur in small isolated pockets within the veins. The shape of the more heavily mineralized portions of the veins is that of an irregular, relatively shallow blanket with three root-like projections that extend downward into the region of sparse mineralization, as illustrated in the longitudinal projection, Figure 3. The three "roots" of the ore body appear to mark the original major channelways along which the hydrothermal fluid passed in greatest abundance.

There are striking differences in the mineralization within as contrasted with outside these major channelways. Within these roots, now marked by high-grade gold ore, deposition has been largely by non-selective replacement. In these areas, all rock types and early gangue minerals have been replaced with equal ease by the gangue minerals and the sulfides of the later phases of the ore-forming period. The larger part of the material deposited here is apparently magmatically derived, and the process of deposition has been one of wholesale replacement. In the sparsely mineralized stretches between the ore shoots, replacement has been limited and extremely selective, and all material except small amounts of auriferous pyrite appears to have been locally derived. In these outlying areas of the veins, mineralization involved the local reworking of rock minerals with only minor introduction of material

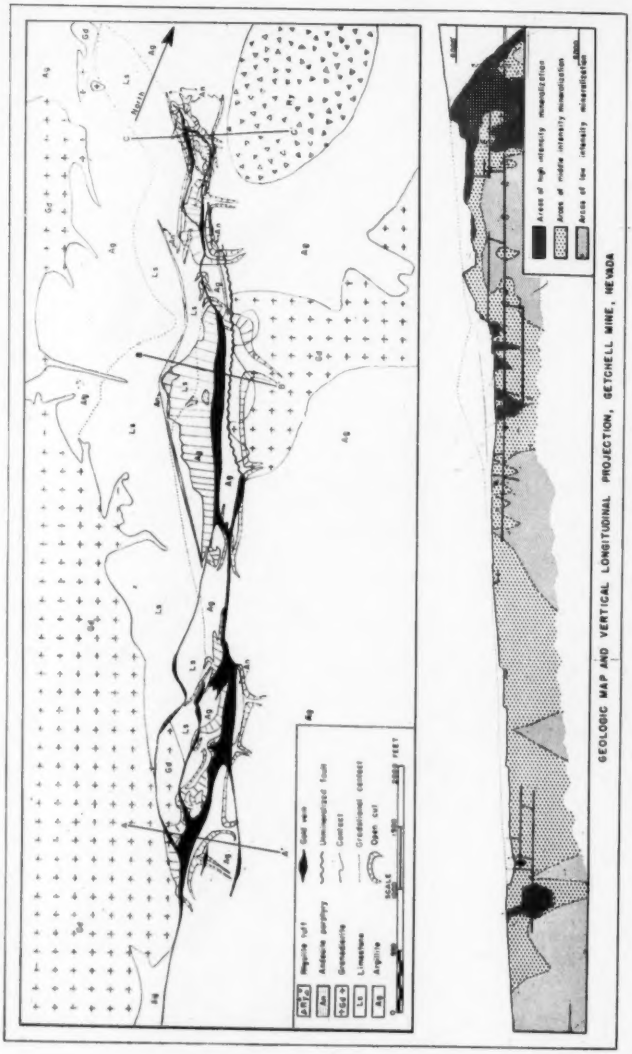


FIG. 3. Geologic map and vertical longitudinal projection, Getchell mine, Nevada.

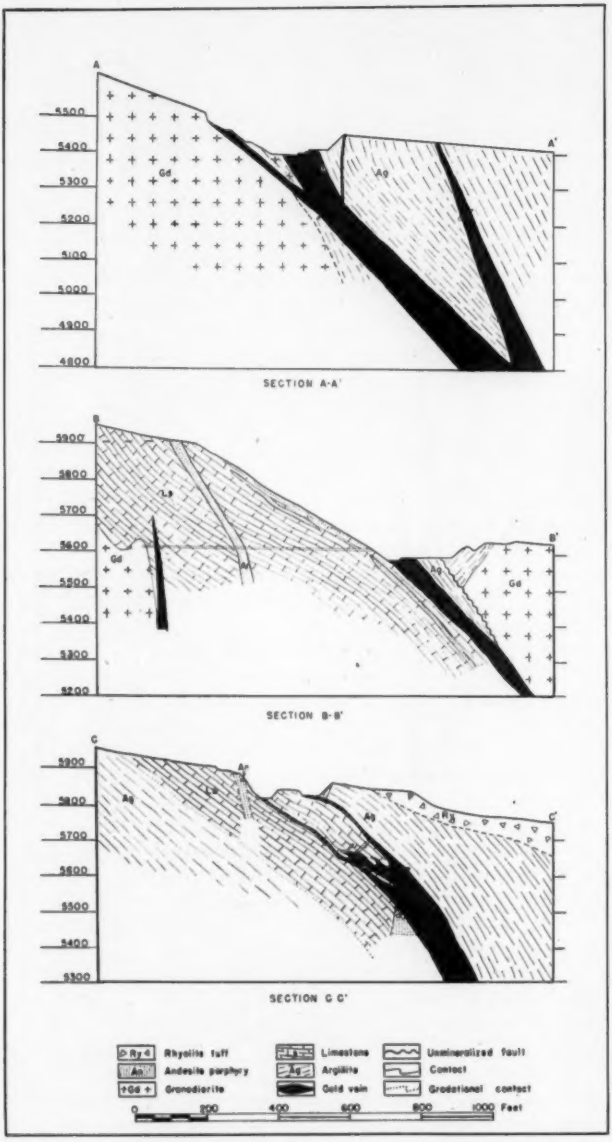


FIG. 4. Geologic cross-section through Getchell ore body.

foreign to the rocks. Thus, calcite veins are restricted to beds of limestone and quartz veins and lenses occur only in argillite.

The gumbo, the important gold-bearer, is unusual in that while it appears to be a fault gouge, it actually consists of minute subhedral quartz crystals embedded in a nearly submicroscopic intergrowth of quartz and amorphous carbon (Figs. 9, 11, 12, 14). In places veins of gumbo several feet wide and parallel to the surrounding sedimentary rocks end abruptly against unsheared limestone or argillite. That it is of hydrothermal origin is indicated by the fact that in thin section it appears actually to replace the wall rock, as shown in Figures 8, 9, and 10. It was apparently formed in two stages. First was the replacement of wall rock by fine-grained quartz to form a porous aggregate of subhedral quartz crystals in narrow bedding veins. In the second stage, carbon, probably derived from underlying argillite, was introduced into the porous quartz veins and was deposited interstitially to the quartz. Rather surprisingly, those portions of the veins that contained the most gumbo and would ordinarily be considered to be but slightly permeable, remained the most permeable sections of the veins and the later hydrothermal solutions were there concentrated.

Metalliferous Minerals.—The deposition of important amounts of gangue minerals had apparently stopped by the time of maximum deposition of sulfides. Pyrite and minor pyrrhotite are the earliest sulfides and in the ore shoots they occur in irregular porous masses, as shown in Figure 26. In the outlying segments of the veins pyrite has a tendency to assume euhedral forms. Replacement has been the important mechanism of deposition of all later sulfides within the ore shoots (Fig. 12) whereas fracture-filling is predominant in the sparsely mineralized zones (Fig. 13).

Arsenopyrite is present in minute euhedral crystals and is almost entirely restricted to the portions of the veins occurring in the andesite porphyry.

Marcasite constitutes about 5 percent of the iron sulfides in the central channelways but is rare or non-existent in the outlying areas. It occurs as minute laths and as irregular shells or rims encircling earlier pyrite grains.

Arsenic sulfides are the most abundant of the metalliferous minerals and, unlike pyrite, are entirely restricted to the areas within the veins that now contain noteworthy quantities of gold. Orpiment is apparently earlier than realgar and is found only in isolated pockets, characteristically occurring in low-grade sections of the veins. In these pockets, orpiment constitutes as much as 40 percent of the mineralized material and is veined and coated by realgar. Realgar occurs throughout the commercial ore bodies in amounts ranging from 1 to 10 percent. It shows such a consistent relation to gold that the presence of realgar is usually a strong indication of good values.

Stibnite, like orpiment, occurs in restricted pockets in which it is present in two unusual forms. Stibnite occurring in narrow, pipe-like bodies is present in a series of clusters of hair-like crystals so minute as to suggest a soft black velvet coating on the rocks. The molybdenum mineral ilsemannite is closely associated with this stibnite. In one small area the fractures in the rock are coated with metastibnite, a red paint or stain which has been shown by X-ray photographs to be finely dispersed stibnite. Similar forms of

stibnite have been found in the sinter and the hot spring muds at Steamboat, Nevada (4).

Cinnabar is present as a thin coating on calcite and chabazite crystals in a narrow and discontinuous branch vein. While it does not occur in com-

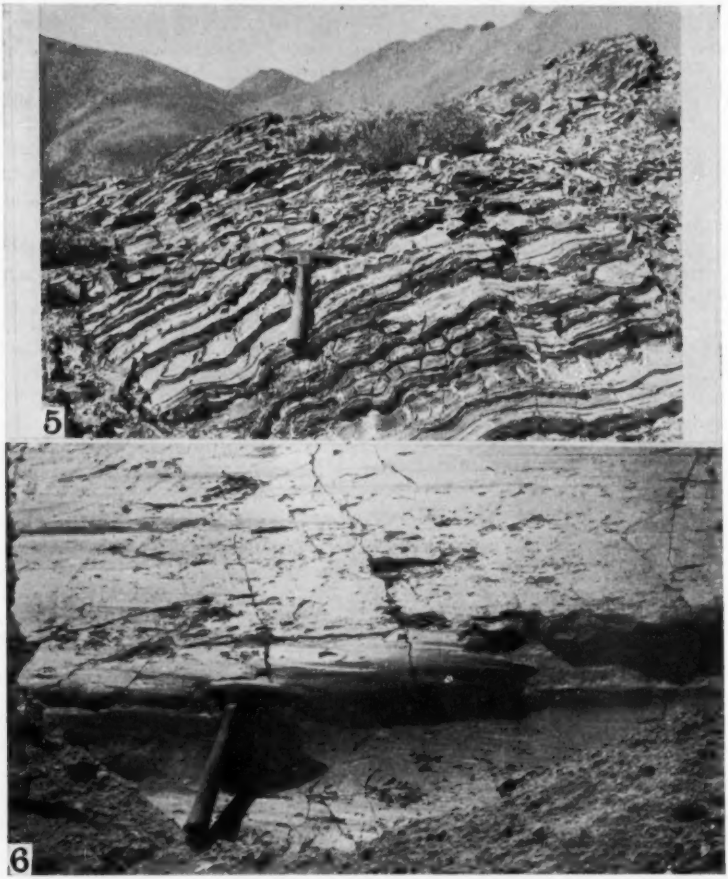


FIG. 5. Interbedded limestone and argillite from Getchell mine area. The vein material has replaced portions of this formation, preserving the thinly laminated structure.

FIG. 6. Fault surface that forms the foot-wall strand of the Getchell vein system. The nearly horizontal mullion structure is strong evidence in favor of horizontal fault displacement along this surface.

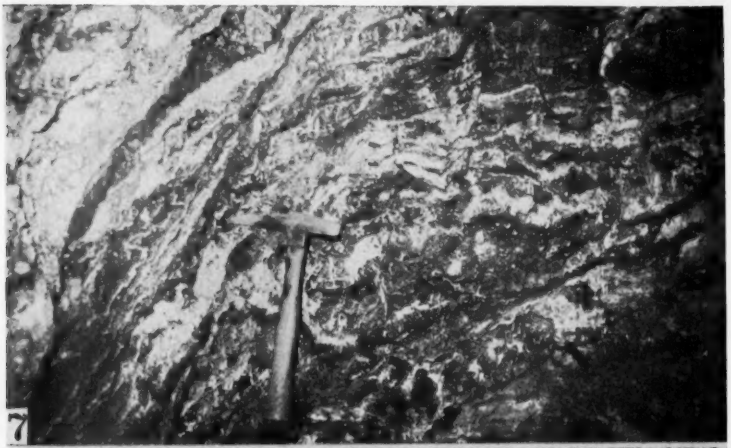


FIG. 7 Typical vein material. Realgar veins, appearing as white bands, preserve the sedimentary structure. The black bands are of carbonaceous gumbo and unreplaced linestone and argillite. A minor pre-mineral normal fault cuts and warps the bedding.

FIG. 8. Photomicrograph of thin section of vein material, showing incipient silicification of argillite. The fine-grained argillite shown in the lower half of the picture has been replaced by coarse quartz grains. In the process of this replacement the carbon has been largely removed. The texture of the replacing quartz grains is similar to that of the quartz in the rich ore gumbo. Cross nicols, × 50.

mercial quantities, its very presence suggests a possible genetic relation between Getchell and the cinnabar deposits of Nevada.

Magnetite is apparently the latest of the metalliferous minerals associated with gold, and is the one most closely related to gold. It occurs only in microscopic particles and has been seen only in the gumbo and andesite. It is plainly not a detrital mineral. It is so closely associated with gold that any polished sections containing a cluster of magnetite grains have also some gold close at hand, generally within a millimeter (Figs. 22, 23).

PRECIOUS METALS.

Distribution.

Economic amounts of gold are entirely restricted to the veins, within which the richer ore shoots are loci of more intense mineralization. The richer gold ore is in the shape of a relatively shallow, discontinuous blanket with three root-like downward projections, as illustrated in the projection in Figure 3. The cause of localization of the ore shoots is discussed in a later section. The portions of the veins between the rich shoots, and the wall rock for several hundred feet on either side of the veins contain everywhere a small amount of gold, ranging from 0.01 to 0.08 ounces per ton. The commercial gold ore has been developed over a strike length of 7,200 feet and to a depth of as much as 800 feet. At this depth, rich gold ore is still present.

Visible Gold.

Because of the crumbly, non-cohesive nature of the gumbo, it was necessary in polishing specimens of the ore for microscopic investigation to develop a technique which would allow the polishing of even the smallest particles of gold. Mr. Charles Fletcher of the Laboratory of Mining Geology at Harvard University prepared the polished sections and his patience and skill have aided immeasurably in this investigation.

In the early stages of the microscopic study, extremely few gold particles were to be seen, and it became apparent that the polishing methods in use were not satisfactory for this problem. The polishing treatment finally adopted represents the results of progressive trials and improvements. In this process, the sample to be polished is first impregnated with a liquid bakelite resinoid and then baked. It is next sawed and is again impregnated. Following this it is placed in a bakelite briquette, and is ground to a smooth surface. After a final impregnation, it is ready for the several stages of polishing on the Graton-Vanderwilt polishing machine. The multiple impregnation is necessary because a single impregnation penetrates only a short distance into the section. By using this method of polishing and by using a microscope with a Zeiss 2-millimeter objective lens, N.A. 140, mineral grains having an area of as little as 0.1 square microns are visible and recognizable.

The properties of gold are so diagnostic as to make it an ideal subject for such a detailed study. Its brilliant yellow color makes it easily recognized in larger particles but when the grain size decreases to a diameter of less than

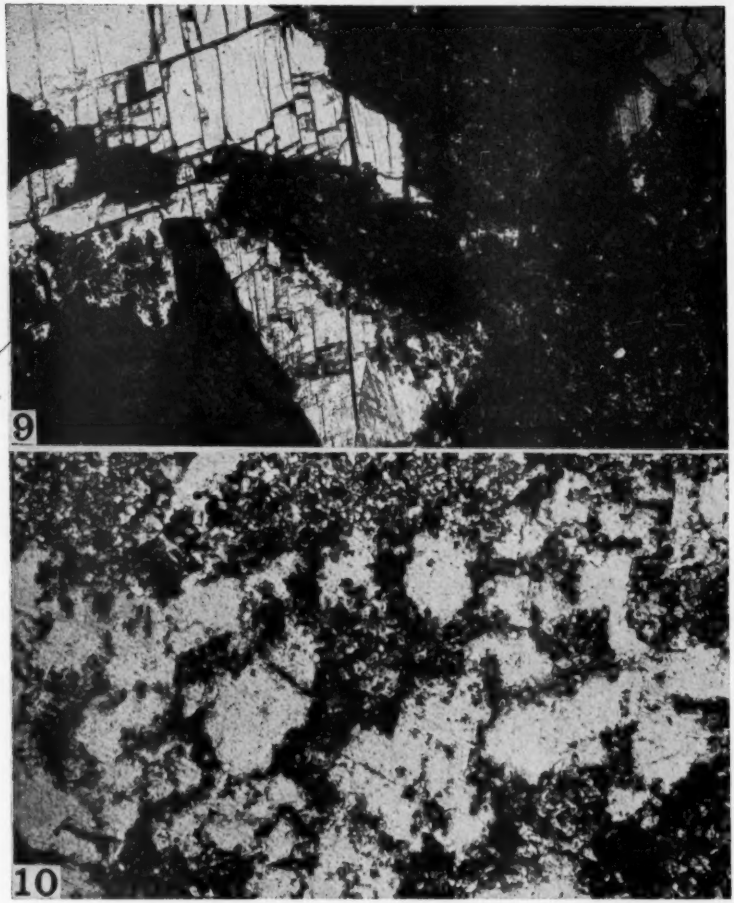


FIG. 9. Photomicrograph of this section of vein material in limestone. The white, coarse-grained calcite is replaced by the carbon-rich ore gumbo that appears black, and by realgar, the shattered mineral in the lower left. Cross nicols, × 50.

FIG. 10. Photomicrograph of thin section of coarse calcite partially replaced by high-grade ore gumbo. The calcite in the irregularly mottled grains shows the same extinction over the entire section and represents isolated remnants of a once much coarser grain. Quartz occurs in the small clear grains and the black material is carbon. The texture of the replacing gumbo is typical of the richer material. Cross nicols, × 48.

one micron, the color becomes less noticeable and other features must be used for identification of minute particles. The extreme softness of gold prevents the achievement of a perfect polish on small grains, but every minute grain of gold has a characteristic undulant, "egg-shell" texture (Figs. 24, 25, 26). Gold is exceeded in reflectivity only by native silver, platinum, and copper, and the egg-shell texture may be used for positive identification of all particles to a limit of microscopic visibility at a magnification of × 2,500.

The described polishing technique is probably not perfect; indeed it is reasonably certain that some grains that would have been above the limit of visibility, had they remained in place and been polished, were torn from the polished surface. The proportion of grains thus lost undoubtedly would increase as the grains became smaller. Furthermore, some grains of visible size may not have been seen. Even with the most careful polishing, the extreme softness of gold makes inevitable its depression below the impregnated surroundings. Hence there is an oblique band around every gold grain that gives no reflection up the tube of the microscope. The *width* of this band is a function of the relative softness of gold to its surroundings and thus tends to be independent of grain size; but the *relative importance* of this relief shadow increases with decreasing size of gold grain. If the diameter limit of visibility of a grain of gold ideally polished is "x," and the width of the oblique shadow in actual polishing is "y," then an imperfectly polished grain must have a diameter of $x + 2y$ to be visible. All grains smaller than this would appear only as tiny black pits.

Finally it is certain that not all grains possessing a true diameter above the ideal limit of visibility that were actually present at the plane of polish were seen. This plane must have touched many grains, large and small, so far from their equator of maximum diameter that the intercept at the plane of polish did not attain practical visibility.

In this investigation, more than 2,600 gold particles were identified and measured. The results of these measurements are given in Figure 17. The graph shows the enormous increase in the abundance of gold particles with decreasing grain size. It also shows that the great bulk of the gold is in the rare and widely scattered larger particles having an exposed area of more than 1,000 square microns.

All gold particles seen in the Getchell ore are roughly lenticular in cross-section. To get a better idea of the three dimensional shape of the particles, the length and width of individual grains visible on the polished section were measured and, after further polishing away a measured thickness from the section, the dimensions of the same grains were remeasured; this procedure was repeated, step by step, at about 2-micron depth intervals, until one after another of the grains disappeared. It is apparent that the gold particles are lenticular in three as well as two dimensions. Knowing the approximate dimensions of individual grains and the number of grains visible on every polished surface, it is possible to estimate the minimum gold content of the polished specimen and to compare it with the assay value of the specimen from which the section was prepared.

The average polished section may be regarded as a rectangular block with dimensions $2 \times 1 \times 1$ centimeters. Each block weighs about 2.7 grams and 336,000 such blocks would be required to make a ton of ore. Gold with some silver present has a specific gravity of about 17.3. One cubic centimeter of gold weighs 0.556 Troy ounces, and ore containing 0.5 ounces of gold per ton must contain 0.9 cubic centimeters of gold. If the gold occurred in cubes one centimeter on an edge, an enormous number of polished sections might have to be prepared before this gold would be encountered. If the assumption is made, however, that gold is present in grains having an average dimension of $1 \times 1 \times \frac{1}{2}$ microns and is so distributed through the ore that each mass the size of a polished section holds a representative amount, then one ton of ore containing 0.5 ounces of gold would contain 2×10^{12} grains of gold. Every polished section block would contain an average of 5.94×10^{6} gold particles. Because of the abundance of non-opaque minerals in the Getchell ore, it is possible to see not only minerals actually cut by the polished surface but also minerals lying as much as one micron beneath the surface. Thus each polished section may be visualized as being divided into a series of flat sheets one micron thick. Every sheet would contain 1,045 particles of gold. There are many assumptions in these calculations, but the results give at least a rough idea of the number of gold particles one might expect to see if all gold occurred in visible grains of the size specified. Increasing size of grains greatly reduces the number.

The investigation of particle size and number has shown that there is little correlation between the assay value of the sample and the calculated value of the polished section. As an example, five polished sections were prepared from an ore sample which was shown by assay to contain 1.06 ounces of gold per ton. In one of these sections, fewer than 20 gold particles of micron size or larger were seen, while another contained more than 800 particles of the same or larger size. The other three varied widely but fell within these limits. The conclusion must be reached that the gold is not regularly distributed, even in a small sample, but rather that it is strongly concentrated in certain bands and lenses about one centimeter wide. The five sections mentioned above were all prepared from gumbo, so this spotty gold distribution is apparent even within the gumbo which is generally an excellent indicator of rich ore.

Most of the visible gold is intimately associated with the fine-grained quartz-carbon matrix of the gumbo. Many of the particles partially rim larger quartz grains. Some of the gold is rather uniformly distributed throughout the gumbo in small isolated particles. This is slightly more abundant in those bands in the ore that contain more carbonaceous material. These particles average 4 square microns in exposed area, somewhat larger than the average of all visible grains. In addition to the uniformly but sparsely distributed particles, gold grains also occur in clusters of roughly lenticular outline (Figs. 27, 28). These gold-rich pods are composed of abundant gold grains that average one half of a square micron in exposed area. They are commonly so abundant that under low power magnification the entire area of the lens has a pale yellow color. Yet within the lenses gold occupies less than 1 percent of the area. Like the individual grains mentioned above, this gold occurs in

the carbonaceous matrix, and quartz grains within the gold pods stand out as barren islands. The lenses are as much as 100 microns wide and are commonly several millimeters long. These aggregates of gold particles have been seen only within the gumbo and are commonly elongate parallel to the structure of the gumbo. Even within the gumbo, these lenses are rare and the presence of one or two in a sample will give an erratic high assay.

Gold in these pods is intimately associated with magnetite and carbonaceous matter. Magnetite is slightly more abundant than gold and, like gold, is very loosely embedded in the matrix and is easily removed by rubbing. During the impregnation of the polished sections, both magnetite and gold from some of these lenses were pulled out from the carbonaceous matrix by the inrush of resinoid after evacuation and were carried along open cracks in the section, finally forming inclusions in veinlets of resinoid. This magnetite seldom shows a euhedral form and generally occurs in irregularly rounded masses and angular fragments. It is largely restricted to the gumbo. Rarely, both gold and magnetite are rimmed by a mamillary halo of carbon (Fig. 23). There is thus a strong suggestion that there has been a redistribution of small amounts of carbon during or after the main period of gold and magnetite deposition. Magnetite occurs not only in the rich gold lenses but also disseminated through the gumbo in small isolated grains. No magnetite has been seen outside of the ore bodies.

In addition to the occurrences discussed above, gold is found rarely as inclusions in the sulfides. All of the major sulfides contain some visible gold, but pyrite and marcasite are the principal hosts. Less than 1 percent of the total number of gold particles seen occurs in sulfides. It may be that the larger gold particles were deposited almost entirely in the gangue, but there is some evidence to suggest that such is not the case. The gold particles occurring in the sulfides are far more loosely held than that in the gangue. The particles in the sulfides that were not wrested from the surface during grinding and polishing are invariably removed when the immersion oil is wiped from the section. So it is probable that the sulfides contain far more gold of visible size than can be seen in polished sections.

All forms of pyrite and marcasite contain some visible gold, but the more porous varieties are more commonly hosts for the metal (Figs. 25, 26). Where gold particles occur as inclusions in subhedral crystals of pyrite they are generally in the outer parts of the crystals. None has been seen in the cores of these crystals.

Summary of Occurrence of Visible Gold.—Visible gold occurs sparsely disseminated through every rock type in the veins and is particularly abundant in the gumbo. Gold distribution is quite similar to that of marcasite and realgar, and is more restricted than pyrite. The only minerals that are strikingly associated with gold are carbon and magnetite. Laboratory tests show a strong direct relation between carbon and gold, and the gold content of carbon concentrates increases as the purity of the concentrate is increased.

The size of the particles of visible gold ranges from a fraction of a micron to nearly one millimeter; the smaller grains are far more abundant than the

larger. The weight-distribution curve shown by the broken line in Figure 17 shows that the larger part of the mass of gold is from the less abundant, larger particles.

The more porous forms of the sulfides contain more gold than the solid euhedral crystals. There is apparently a strong, direct correlation between the amount of surface exposed in the host minerals, that is, the porosity, and the amount of contained invisible gold.

"Invisible" Gold.

It is probable that not all the gold occurs in visible grains. The "invisible" gold may occur in any of three forms. First, it may occur in the native state in particles below the limit of microscopic visibility. Second, it may be present in a compound such as the telluride, likewise submicroscopic or else undetected. Finally, it may occur in solid solution with the sulfides or adsorbed onto the surfaces of carbon and the sulfides. This may be visualized as a two- or three-dimensional solution, depending on whether gold was adsorbed onto the host structure after or during the growth of the latter. An adsorbed film of gold on a pre-formed mineral differs from gold in atomic dispersion through the host mineral structure only in that it is a planar rather than a three-dimensional feature.

The frequency distribution chart in Figure 28 has been prepared on a logarithmic scale. This chart shows the great range in size between the gold atom and the smallest visible particle.

Gold in Solid Solution in Sulfides.—According to present theory, two major types of solid solution occur in nature. First is substitutional solid solution. In this, ions of the minor (guest or solute) component occupy the position in the crystal lattice that would be normal for ions of the dominant (host or solvent) component. Depending on whether the radius of the guest is larger or smaller than that of the host, there will be an expansion or contraction of the resulting crystal structure. As the difference between the radii of the host and foreign ions decreases, the degree of possible solid solution increases. The growth of such a solid solution is caused by adsorption of foreign ions onto the growing surface of the host. At the surface of a crystal at any stage of its growth there is an unsaturated field of force, since the outermost ions at this stage have not enough neighbors to satisfy their normal coordination. During growth, ions in solution make coordination by attachment to the thin surface of the crystal. A foreign ion in the solution may respond to this field of force and be added to the growing crystal, playing the role of proxy for a dominant ion in the crystal, provided that the radii of the corresponding ions or atoms in question do not vary by more than about 15 percent of the size of the smaller. The covalent radius of the iron ions in pyrite is 1.23 A° and the octahedral covalent radius of gold is 1.40 A° (25, p. 170). So the covalent radius of the gold ion is within 15 percent of that of iron, and gold should be able to enter into substitutional solid solution in pyrite.

The second type of solid solution is known as interstitial solid solution. In this, the solute atoms are believed to be dispersed in the structure of the

solvent atoms or ions. The solute or foreign atoms are introduced in addition to, rather than in place of, the host or solvent ions. This type of solid solution is rare and generally occurs where the foreign ion is distinctly smaller than the host.

Synthetic Auriferous Pyrite.—Maslenitsky (22) added gold chloride and colloidal gold in the course of synthesis of pyrite. He was able to control the amount of gold contained in the pyrite up to a maximum amount of about 9.7

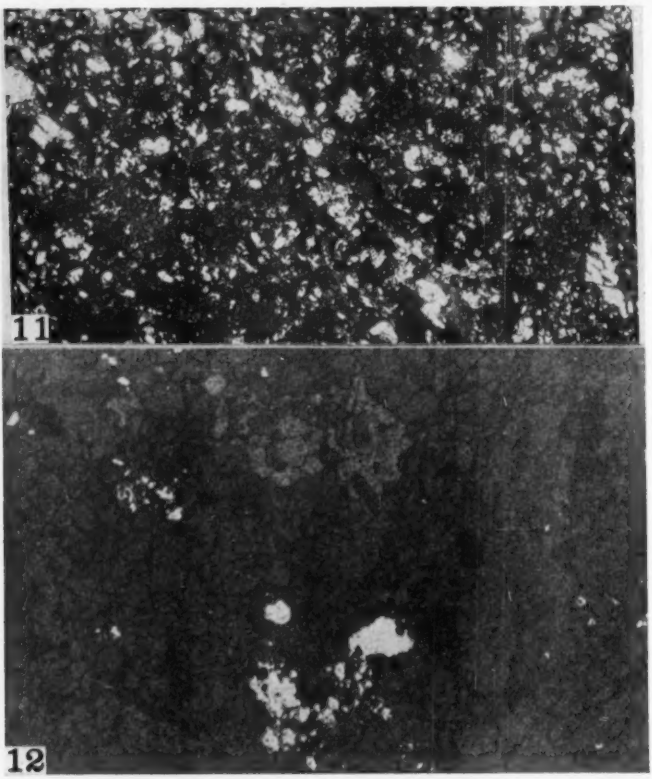


FIG. 11. Photomicrograph of high-grade gumbo. The nearly uniform size of the quartz grains is characteristic of the richer material. All quartz grains are embedded in carbon. Although the host rock has been entirely replaced, the sedimentary structure has been preserved. Cross nicols, × 40.

FIG. 12. Photomicrograph of polished section of ore gumbo. Pyrite (white) and realgar (light gray) have replaced the fine-grained quartz-carbon intergrowth interstitial to the larger quartz grains, leaving the latter as residual islands. This gangue texture is typical of all high-grade portions of the ore. × 45.

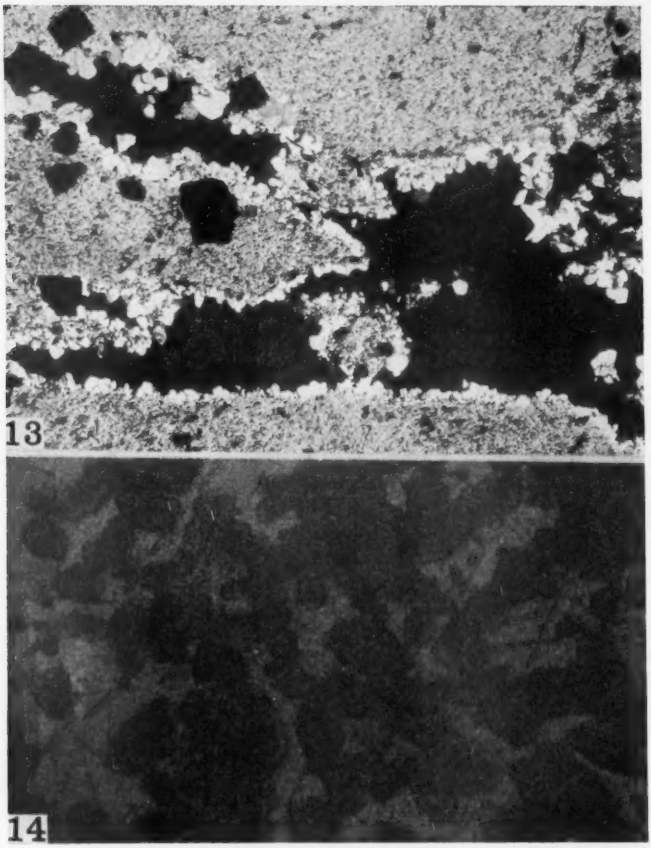


FIG. 13. Thin section of realgar and vein stuff. The realgar appears black in the forked vein that is rimmed by thin layers of quartz crystals. The black euhedral crystals outside the vein are of pyrite. The vein cuts a fine-grained quartz-sericite intergrowth that is an unreplaced fragment of argillite. Such material is not a conspicuous gold-carrier. Cross nicols, × 40.

FIG. 14. Photomicrograph of polished section of realgar in ore gumbo. The realgar (light gray) surrounds islands of subhedral quartz crystals, having replaced the fine-grained quartz-carbon matrix of these grains. × 310.

ounces per ton. Investigation of the auriferous pyrite under × 1,200 magnification revealed no gold and the gold may have been in solid solution in the pyrite. The method of polishing used in the preparation of these polished sections is not known. In many cases specimens that reveal no gold when

polished on a cloth lap may be shown to contain abundant visible gold after repolishing on a lead lap.

Kuranti (18) prepared a synthetic auriferous pyrite in which gold was invisible even under the highest magnification possible. Again the method of polishing may have obscured some visible gold. The gold was shown by spectrographic analysis to be distributed uniformly throughout the pyrite, and X-ray pictures of the pyrite showed that the pyrite lattice constant varied with increasing gold content, reaching a constant value at 2,000 grams of gold per ton of pyrite. The evidence may indicate that solid solution of gold in pyrite is possible. Unfortunately the original Japanese publication describing this work is not available.

Natural Auriferous Pyrite.—It is probable that gold in solid solution in pyrite may be synthesized. A naturally occuring example of such solid solution has not been previously described, although many writers have attacked the problem.

R. E. Head (15) suggested that at least some gold in particles of micronic diameter in pyrite occurs in tiny leaves or flakes coated with a magnetic iron mineral, lying between crystallographic planes in the pyrite. Such a feature might suggest exsolution of gold. Edwards (6, p. 130) states that such fine gold particles rarely show the ordered arrangement in the pyrite that would be expected if this were so.

Haycock (14) prepared a frequency-distribution chart of sizes of gold particles in 50 Canadian ores, and found that the greatest number of grains were well within the range of microscopic visibility. Over 75 percent of all the visible gold falls within the microscopic rather than the megascopic range. By projecting this curve into the range of submicroscopic sizes, Haycock concludes that gold of colloidal sizes has only slight importance and gold in solid solution in sulfides may be of even less economic value. He points out that until the natural existence of gold in solid solution in pyrite or other sulfides is proved to be significant, it is more in accord with probability to stress the importance of normal gold particles of submicroscopic size.

Auger (2) studied pyrite from various gold deposits in Canada. He made spectrographic analyses of the pyrite and found that the spectral gold lines were inconsistent, even within one deposit. He concluded that gold, whenever present, is unevenly distributed in the pyrite crystals and appears in the spectrum only when the analyzed sample contains small particles of gold. Auger felt that this evidence strongly suggests that gold does not take part in the structure of the pyrite crystal as solid solution, and that gold is not precipitated at the same time as the pyrite. His study included only natural pyrite and his conclusions do not constitute a denial of the possibility of gold in solid solution in pyrite. It might be well to mention that gold is relatively insensitive to spectrographic analysis, as the lower limit of sensitivity is about 0.001 percent.

Pyrite and arsenopyrite from the Dolphin East Lode, Fiji (28), were found to contain as much as 33 ounces of gold per ton, although only a few particles could be seen microscopically. The sulfides were heated to 600°

C and, on cooling, were again examined microscopically. Abundant gold particles, enlarged to visible size by the heating, were formed by the coalescence of submicroscopic gold. Stillwell interprets these results as an indication of the presence of gold in limited solid solution in the sulfides. Heating of the gold-bearing pyrite, however, would tend to preserve, rather than terminate, any state of solid solution. It is perhaps more probable that this Fiji gold is present in independent particles larger than the gold unit cell. The coalescence of smaller particles represents a change to a form having a lower, and thus more stable, surface energy, if the original gold is in colloidal-sized particles.

Back-reflection X-ray photographs of pyrite from Amador, California, taken at Harvard, show that the structure of some of the pyrite is distorted, having a cube edge of 5.477 kx, while other of the pyrite has the normal undistorted structure with A_0 equalling 5.405 kx. Spectrographic analyses indicate that the distorted material contains about 5 ounces of gold per ton, approximately ten times as much as is contained in the normal material. While both types of pyrite appear to be the same in polished section, nitric acid brings out a differential etch pattern, the auriferous pyrite being etched more deeply than the lower grade material. This evidence strongly suggests that at least some of the Amador gold is in solid solution with the pyrite.

Similar etching or tarnishing was noted at the Simmer and Jack Mine on the Rand some years ago (12). At that deposit, and at adjacent mines, it was found that one of the dependable signs of better-than-average gold values in the Reef was the rapidity of tarnish of the pyrite at those places. The pyrite of rich stretches of the conglomerate would develop strong irridescence on a freshly blasted face within a day or two. This differential tarnish may have been brought about by the presence of gold in solid solution in some of the pyrite.

Auriferous Pyrite in Getchell Ore.—Pyrite from the ore shoots in the Getchell mine contains some small particles of visible gold, commonly located near the edges of the pyrite grains or near open spaces within the grains. Further gold has apparently been lost during polishing. It is probable, however, that the gold of visible sizes is not abundant enough to account for the total gold value of the pyrite. No visible gold has been seen in polished sections of pyritic concentrates from the ore, although they contain about 0.5 ounces of gold per ton.

Samples of the sulfide concentrates were heated to 600° C in the presence of sulfur vapor in a sealed tube. Each polished section prepared from this material reveals from 10 to 20 particles of gold averaging 0.3 microns in diameter. All particles occur at the boundaries of pyrite grains (Fig. 24). Heating of the pyrite apparently brought about two related processes. First, it caused the submicroscopic gold to migrate toward the margin of the host grains, thus ridding the bulk of the pyrite of its gold. Second, the heating caused the coalescence of the gold present to form, in some instances, visible grains. This heating process cannot be assumed to make all the grains visible; probably only the richer pyrite grains contained enough gold to yield visible particles. This experiment suggests that the pyrite may not contain uniform

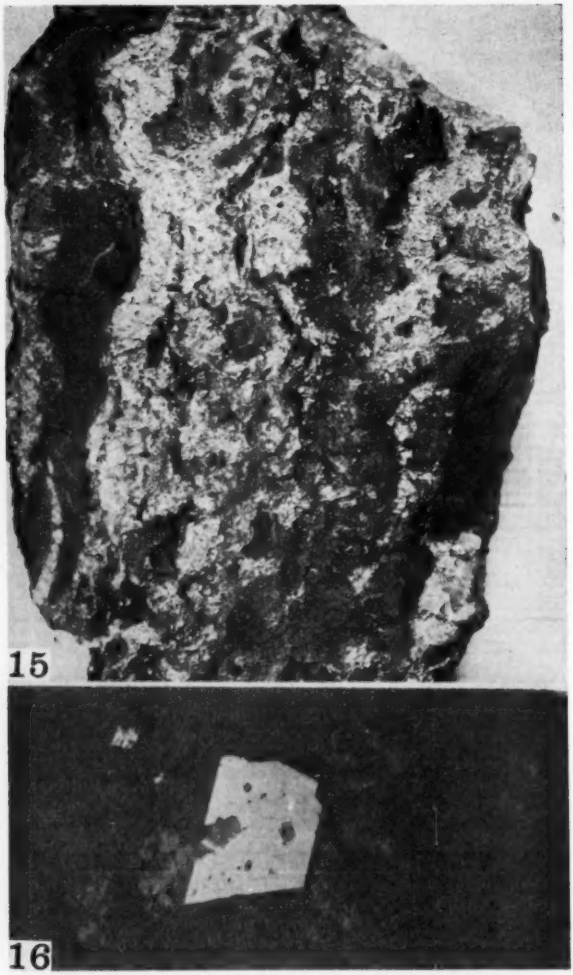


FIG. 15. Hand specimen of typical gold ore. The light material is realgar, occurring as bedding veins in limestone. Irregular patches of gumbo have also replaced the limestone. About half natural size.

FIG. 16. Photomicrograph of polished section of ore in andesite porphyry. The white euhedral crystal is arsenopyrite and the irregular light gray mass is magnetite. Magnetite apparently has replaced both the gangue minerals and arsenopyrite. × 425.

amounts of gold, although, as previously stated, all pyrite contains some gold. Grain size of the pyrite is apparently not an important factor in determining the amount of contained gold; large grains show no more tendency to contain visible gold than do the smaller particles. This experiment proves the existence of submicroscopic gold in the pyrite, but it does not prove or even suggest whether the gold occurs in atomic or ionic division or in particles with dimensions exceeding those of the gold unit cell.

A comparison between auriferous pyrite and artificially prepared activated charcoal containing gold may seem extreme, but a brief description of the charcoal and its effects on gold may shed some light on the problem of auriferous pyrite. Metallurgists have long been aware of the fact that charcoal is able to adsorb gold selectively from a complex solution. This property is utilized at the Getchell mine where activated charcoal is used to remove gold from cyanide solutions. The charcoal probably adsorbs gold in the form of a double cyanide with sodium or calcium.

Gross and Scott (13), largely on the basis of chemical tests, found evidence suggesting that the gold adsorbed on the activated charcoal was not in the metallic state. However, polished sections of treated charcoal containing nearly 200 ounces of gold per ton were prepared at the Harvard Laboratory of Mining Geology, and in these, abundant metallic gold was found present in small but visible particles (Fig. 27). It is possible that the adsorbed gold cyanide salt, being extremely unstable, may have broken down to metallic gold after standing for some months. Such a breakdown, however, would probably form extremely minute particles and it is apparent that the gold seen in the polished sections of the charcoal is too coarse-grained to have been formed in this way. So some other factor may have brought about the coalescence to visible size. Whatever this force may be, it is strong enough to overcome the adsorptive attraction of the charcoal for the gold, as the adsorbed ions appear to have been pulled from the carbon surface to form larger particles. It is also possible that the first gold adsorbed on the charcoal acted later as nuclei for the growth of metallic gold particles. The first layer or film of gold atoms is assumed to have been deposited by adsorption, while further growth may have been accomplished by normal forces of crystallization.

Like the visible gold in the sulfides, these gold particles are extremely loosely held on the surface of the charcoal and but few can escape removal during polishing. The gold particles in the charcoal and pyrite alike occur either along the margins of the host grains or bordering minute open spaces within the grains. In the case of the charcoal, the amount of gold that can be adsorbed varies with the exposed surface of the charcoal, and most gold occurs in the more porous material.

It may be merely coincidence that the pyrite and marcasite in the richest ore are porous and have irregular surfaces, whereas the pyrite that occurs away from the ore shoots is generally more solid and more regular in outline. But the fact that visible gold associated with sulfides generally occurs in the irregular, porous forms of the sulfides suggests that this porosity may have been important in localizing the gold. Laboratory tests have shown that a sub-

stantial part of the gold occurring with the sulfides is associated with the fine-grained portions of the latter. A large grain has less exposed surface than an equivalent volume of small grains, and hence can adsorb less material. An euhedral crystal likewise has less surface area and therefore less adsorptive capacity than an irregular shape of the same volume.

The mechanism of adsorption is here proposed to explain the precipitation of gold on pyrite, other sulfides, and, to a larger extent, on the carbon in the ore. This process differs from that of solid solution in that the latter involves adsorption of the foreign ions *during* the growth of the host. If the bulk of the gold associated with pyrite represents a solid solution of gold in the sulfide, then gold would have been introduced into the ore at the same time as the sulfides, and the amount of gold should be roughly proportional to the amount of sulfides. Most of the gold values, however, are restricted to narrow bands whereas the sulfides are widespread throughout the ore bodies. Thus, it is apparent that the solutions from which the bulk of the gold was deposited travelled along more restricted channelways than did the solutions that deposited the sulfides.

It is not meant to deny the possible existence of gold in a three-dimensional solid solution in the sulfides, but rather to emphasize that any such solid solution can be of only minor importance at Getchell. Indeed, it may well be that a very small amount of gold is in solid solution with the pyrite.

Growth Mechanism of Gold Particles.—If a hydrothermal solution is unsaturated with gold, neither native gold nor any gold minerals may be formed. As was previously mentioned, however, the gold, unable to form its own mineral, may proxy for iron ions in a growing pyrite crystal. Such a proxy would bring about a solid solution of gold in the host crystal. Under these conditions, if the ratio of gold to iron in solution does not exceed the limit of solubility at a given place, all the gold may occur in solid solution in the pyrite. If the ratio is higher, the pyrite will still contain gold in solid solution and will also contain larger gold particles as random inclusions. Where the ratio is much higher, these inclusions will attain visible size.

In any deposit, the physico-chemical conditions, which may be called intensity conditions, may be expected to vary from place to place within the locus of deposition. Thus, a high-intensity zone might be fringed with areas of lower intensity. In the former area, gold would be deposited from hot, concentrated solutions to form discrete particles as well as to occur in solid solution in pyrite. In the outlying, low intensity zones, where deposition was from dilute solutions, the only gold deposited would be that in solid solution in the sulfides.

In the Getchell deposit, the entire zone containing the ore bodies may be visualized as an enormous block of submarginal gold-bearing rock with smaller, superimposed bodies of richer ore, as shown in the projection in Figure 3. The economically worthless sections of the veins and the wall rock contain a rather uniform amount of gold, varying from 0.01 to 0.08 ounces per ton. These low values persist as far into the hanging- and foot-wall country as does the pyrite. Pyrite concentrates from the mine, regardless of the section of the veins from which the pyrite was taken, contain a minimum of about 0.5 ounces

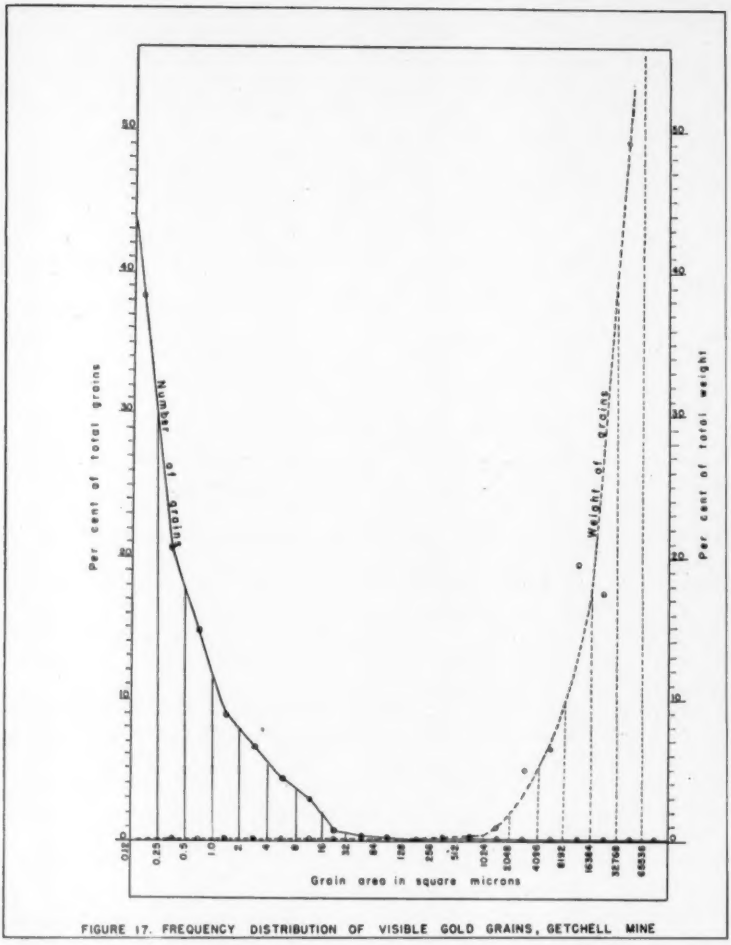


FIG. 17. Frequency distribution of visible gold grains, Getchell mine, based on measurements of 2,639 grains.

of gold per ton. The ratio of concentration of pyrite in the concentrates is about 1:50. Similarly, the ratio of concentration of gold from 0.01 to 0.5 ounces per ton is about 1:50. So the low-grade gold varies directly and closely with the pyrite.

It is to be presumed that the peripheral, submarginal gold and pyrite which

have the same extensive distribution in the wall rock and low-grade portions of the veins are more or less contemporaneous, products of deposition from the low-intensity phase of mineralization. During the growth of the pyrite, and probably also of the marcasite, it is possible that gold was being adsorbed onto the sulfide structure in extremely small amounts. This action may have taken place outside as well as within the ore body.

The extent of solid solution of gold in pyrite must be limited and is probably dependent on the temperature of formation. In a low-intensity deposit such as Getchell, the minimum solubility of gold is probably of the order of 0.5 ounces of gold per ton of pyrite. In parts of the ore body where the temperature of formation of pyrite was somewhat higher than in the areas fringing the ore bodies, the solubility might be higher.

In the outer, low-grade zones at Getchell, the gold-pyrite ratio in the solutions was probably low, and much of the gold appears to have been deposited in solid solution in pyrite. In the central channelways where more intense physico-chemical conditions existed, the ratio and limit of solubility were higher and some gold occurs in visible particles.

Van Aubel (*29*) has concluded that the particle size of native gold is commonly a function of the mode of formation of the associated ore minerals; when gold is contemporaneous with the enclosing minerals it is extremely fine-grained; when it is of later formation it tends to occur in coarser grains. In the Getchell ores, the peripheral gold is in general submicroscopic because only dilute, gold-bearing solutions, exhausted of much of their solute in the course of the long distance travelled from the main channels, were available and the growth of individual gold particles was limited. In the ore shoots where gold deposition from more concentrated solutions continued until the end of the period of mineralization, the gold particles continued to grow, and many achieved microscopically visible size.

The foregoing discussion is admittedly theoretical. It deals largely with that gold, or a part of that gold, which is submicroscopic and is intimately associated with the sulfides. Such gold constitutes only a small proportion of the total that occurs in the richer ore shoots. The writer feels that the evidence favoring the theory of gold in limited solid solution is strong enough to justify considering it.

Conclusions Regarding Gold Occurrence.

Gold at Getchell occurs in particles ranging in size from slightly larger than the gold unit cell to nearly one millimeter in diameter, and probably also in atomic dispersion. Submicroscopic gold is apparently more widespread than the visible metal, occurring throughout the ore body. Microscopically visible gold has a very restricted occurrence and is found only in the richer ore shoots, in which places it accounts for the great bulk of the total gold. The mass of low-grade rock far outweighs that of the ore shoots, and the actual number of submicroscopic particles is probably far greater than that of visible grains.

Discussion has been presented which suggests that the widely distributed but low-grade gold may be mainly in solid solution in the pyrite, whereas the

gold in the ore shoots is surely in discrete particles of the native metal much larger than the gold unit cell. In the very rich portions of the veins, part of the gold is in still larger particles.

The information gathered by measuring visible gold grains and presented in Figure 17 may shed some light on the question of the character of submicroscopic gold. These data have been used in the compilation of the chart in Figure 28. In order to show the full range in sizes, a logarithmic scale has been used on both the ordinate and abcissa. Since the number of grains or particles measured make up a representative sample of all the visible gold particles retained during the polishing, the curve gives an approximation of sizes throughout the ore body.

The curve in the visible range may probably be projected at least some distance into the microscopic field with some degree of reliability. The critical question is whether the curve will drop to zero at or before reaching the area of the gold unit cell following the same general pattern as Haycock's curve (14), or will continue upward along the projection from the known portion of the curve, as indicated in Figure 28.

The submarginal gold values are widely scattered through the ore body, and the mass of submarginal mineralized rock far outweighs that of ore. One ton of rock containing 0.01 ounces of gold contains 2.76×10^{20} gold atoms, and if present in truly atomic dispersion, this enormous figure would represent the number of points at which gold occurs in one ton of low-grade rock. If the gold in the richer ore were contained wholly in spheres of one micron radius, one ton of ore carrying 0.55 ounces of gold would contain 2.38×10^{11} particles. Since the rock containing submarginal gold values is so much more abundant than is the ore, it is probable that the gold in atomic or ionic dispersion is more common than are particles of greater than unit cell dimensions. If, as has been suggested, adsorption has been an active factor in gold deposition, then pyrite and carbon surfaces will contain an adsorbed film of gold ions. In the abundant, lower-grade portions of the ore body where the growth of gold was limited, large particles would not be formed, but much of the gold in the adsorbed films may have acted as nuclei for limited further gold deposition. The number of particles slightly larger than the unit cell would be enormous. In the smaller ore shoots, much of the gold grew to visible size. Granting this, the gold of atomic size is most abundant, the submicroscopic particles are the next most common, and microscopically visible grains are least abundant but represent an overwhelming proportion of the total mass of gold within the ore bodies.

Therefore the curve in Figure 28 might be expected to rise along a more or less straight line through the submicroscopic field toward the unit cell area. If the curve as indicated on the chart is roughly correct, then the frequency distribution of gold particles should be in harmony with the proposed process of gold deposition.

In the marginal phase of mineralization, gold atoms were adsorbed into the pyrite structure during the growth of the latter mineral, and the solutions contained too little gold to allow the growth of metallic gold particles. In

the major channelways the earlier minerals were being displaced upward and outward by the minerals of the more intense phase. In these channelways the solutions were hotter and the gold content was such as to allow the growth of native gold. Here the gold was adsorbed onto the surfaces of the carbon, pyrite, and marcasite to form nuclei for the growth of larger particles. Because the gold concentration in solution was higher in the central channelways than in the outlying areas of the vein and wall rock, the gold formed in this more intense phase would have more opportunity for continued growth. Hence the great bulk of economic amounts of gold is concentrated in these channelways. The ratio of visible to submicroscopic gold is far greater in these channelways than in the low-grade portions of the ore body, and the bulk of the weight of gold is in coarse particles.

The particle size of gold is therefore a function of the length of time of growth and the concentration of gold in solution. The solutions in the outer portions of the ore body contained only very small amounts of gold and there was no opportunity for growth of large particles in those places. The presence of gold particles of colloidal size does not necessarily imply deposition from a colloidal suspension. The chart in Figure 28 intimates that the colloidal-sized particles represent only the dimension attained at a given stage in the normal growth of particles. Every larger particle, being crystalline, must have grown from particles initially of the unit cell dimension.

Cause of Localization of Gold.

Structural Features.—The localization of the three deep "roots" of the rich ore, as shown in vertical projection in Figure 3, suggests that these roots lie along the respective axes of original channelways through which a greater amount of gold-bearing hydrothermal fluid passed. Solutions rising along these channels spread out into a far wider area on reaching the zone of intense shattering near the surface. The three central channelways, one in the north end, one near the center, and one near the south end of the ore bodies, remained as the major channelways throughout the period of gold deposition. Since a larger volume of gold-bearing solutions passed through these channels than through corresponding volumes of rock in the outlying region of shattering, more gold per ton was deposited within the channelways. The gold in the extensive, low-grade portions of the ore bodies is more or less contemporaneous with that in the rich ore shoots, although deposition in the shooots may have continued longer than in the more distant vein material. These richer shoots coincide with the zones of extensive development of gumbo, suggesting that even before gold deposition began, these areas were most permeable to the mineralizing solutions. The gumbo, being unconsolidated, was more permeable, and thus more favorable to transport of the gold-bearing solutions than was the enclosing rock. The concentration of carbon in the gumbo made it a better precipitant than the argillite or limestone.

In the Getchell ore, a small proportion of the total mass of gold occurs in the widespread pyrite, probably because it was deposited as a constituent part of that host. The bulk of the gold, however, is irregularly distributed in every

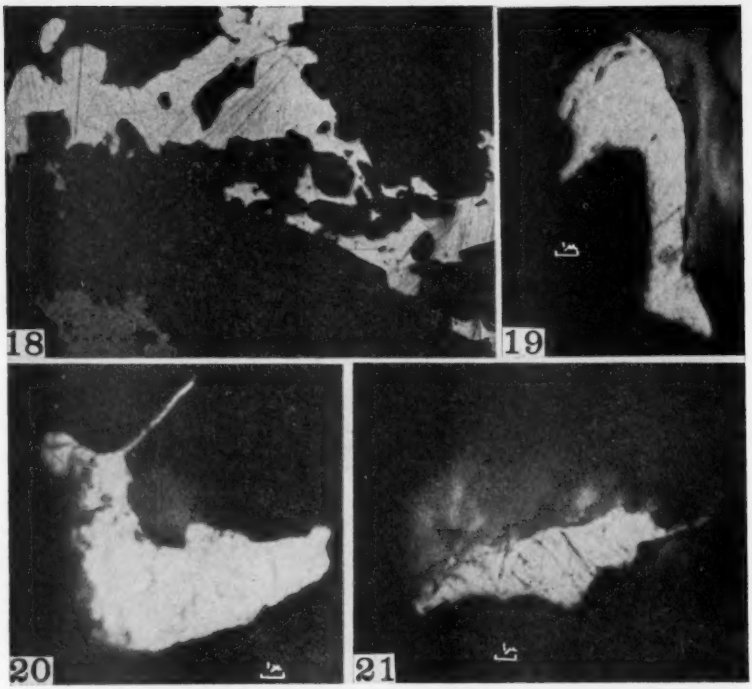


FIG. 18. Photomicrograph of polished section of heavy media concentrate. The large white grains are of native gold and the mottled light gray mineral is realgar. These are the largest gold grains ever seen in Getchell ore, and the only grains found that are megascopically visible. × 70.

FIG. 19. Photomicrograph of polished section of ore gumbo. The large white grain is native gold; a part of this grain is submerged beneath the quartz gangue and appears as an indistinctly lighted area. The irregular mottled surface of the gold grain shows the "egg-shell" texture so characteristic of minute gold grains. × 3,225.

FIG. 20. Photomicrograph of polished section of gold ore, showing a relatively large gold grain that has replaced the fine-grained quartz-carbon matrix to the gumbo, molding itself around the larger subhedral quartz grains. × 3,225.

FIG. 21. Photomicrograph of polished section of gold ore, showing isolated gold grain. The egg-shell texture is apparent. × 3,225.

mineral in the ore body and therefore cannot have been selectively precipitated by any of them. The gold was deposited in or on these various minerals apparently because they had some features in common.

Favorability of Hosts.—Since nearly every mineral in the ore has acted as a host or platform for the gold, the cause of localization of gold is probably a factor common to all minerals. This cannot be crystal structure or chemical

composition. The concentration of gold in the more porous minerals in the ore suggests that this factor may be the amount of surface exposed to the gold-bearing solutions. The mechanism of adsorption discussed in the section on submicroscopic gold may apply to the deposition of gold in or on every mineral. Pyrite (Fig. 26), marcasite, and carbon occur in irregular porous masses with abundant open spaces, whereas realgar, which is more abundant than the other three minerals, characteristically occurs in dense masses with little or no open spaces. As would be expected, realgar is the least important gold bearer.

During the period of mineralization, gold was constantly being carried in solution. In the earlier phase the solutions were too dilute to be saturated with any gold compound, but other minerals, carbon, pyrite, and marcasite in particular, adsorbed small amounts of this metal. Because carbon and marcasite had the greatest surface, they adsorbed the greatest amounts of gold. Gold remained in solution after the deposition of the sulfides was completed, and the process of adsorption continued to act, forming atomic-thin layers of gold on the surfaces of minerals around which the solutions passed. In the later stage of deposition, native gold was deposited in the more permeable parts of the ore shoots where the solutions were more intense and the gold concentration in solution was higher. Adsorption was no longer quantitatively important.

The metallic bond may be visualized as a cloud or atmosphere of electrons interstitial to the metal atoms and holding them in position in the crystal structure. The presence of this electron cloud also brings about an attractive force for metal ions in a solution around the growing crystal. An adsorbed film of metal ions contains interstitial electrons which will attract similar cations in solution. In this way, the thin, adsorbed film of ions may act as a nucleus of growth of larger particles of the metal. So in the important stages of deposition in the Getchell ore, the predominant process was one of normal metal growth on nuclei that had been formed previously by adsorption. The physicochemical conditions at that time were such that gold, no longer stable in solution, was precipitated on earlier formed gold particles. The possible changes in these conditions are discussed in the chapter on genesis.

Native Silver.

A mineral has been seen in many polished sections of Getchell ore which, on account of its physical properties, is taken to be native silver. It is white, isotropic, and has extremely high reflectivity, considerably higher than that of gold; it is very soft, having the same mottled, egg-shell texture that is seen in gold. The only mineral that fits this description is native silver; conclusive chemical tests have not been possible, however, because the particles present are too small. It occurs in sizes analogous to those of gold, although megascopically visible silver has not been found.

The ratio of gold to silver in bullion assays varies from 2:1 to 134:1 and, for the entire bullion production, averages about 10:1. Earlier studies of the ore suggested that the silver probably occurs in electrum, a natural gold-silver

alloy. Only a few particles have been seen in the ore, however, and most of the silver occurs as the native metal.

The silver is probably a hypogene mineral. As the association of native silver and native gold in hydrothermal deposits is rare, the evidence favoring a hypogene origin of the silver must be critically examined. (1) In general the amount of silver in the ore varies inversely with the amount of gold. Extremely rich portions of the ore body contain less silver than the portions of average grade. There is no zonal relation other than this between gold and

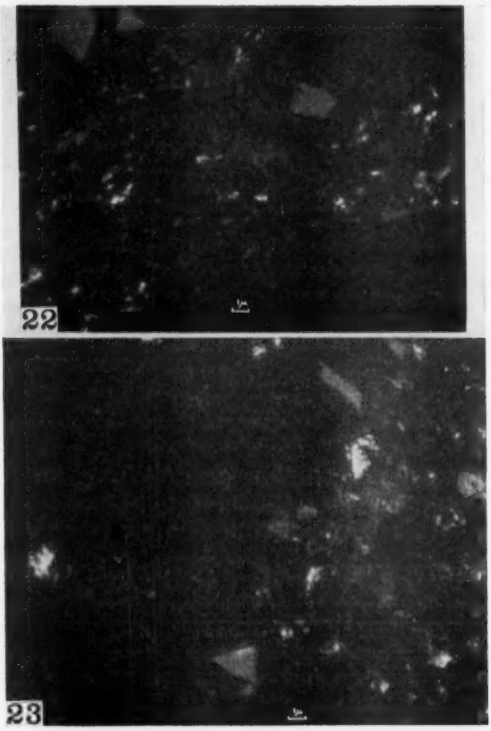


FIG. 22. Photomicrograph of gold-rich carbon veinlet. The small white particles are native gold, and the large, smooth grains are of magnetite. The indistinct gray specks associated with the gold are carbon particles. × 2,275.

FIG. 23. Photomicrograph of polished section of gold ore, showing a gold-rich lens. All white grains are gold. The gray angular fragments are magnetite and the small, irregularly rounded gray particles are carbon. The gold particle on the left is rimmed by a discontinuous halo of carbonaceous matter, as is the magnetite, bottom center. × 2,275.

silver. If silver were a supergene mineral, derived from hypogene electrum, it should be most abundant in the ore richest in gold.

(2) Native silver persists with no large decrease in amount to the deepest levels of the mine. There is no shallow blanket of richer than average silver ore, as would be expected if the silver were supergene.

(3) Silver particles show the same variations in grain size as the gold particles. If silver were supergene, formed under totally different conditions from those in which gold was formed, it would be unlikely to occur in grains of approximately the same size as the gold particles. Had silver been derived from electrum by meteoric leaching, the residual gold would be expected to occur in porous masses, but the gold particles are solid.

(4) Like gold, silver occurs in the carbonaceous matrix of the gumbo and in sulfides, particularly the porous pyrite-marcasite intergrowths. It is loosely held in the host minerals and is easily removed by rubbing. Unlike gold, silver particles do not occur in lenticular aggregates. Otherwise the habit of silver closely resembles that of the widespread but sparsely disseminated gold particles, and the periods of deposition of silver and this gold were probably overlapping.

Why silver did not more commonly unite with gold to form electrum is not clear. Gold in most low-intensity deposits contains a considerable amount of alloyed silver. At the Getchell mine, however, even the gold and silver that, on the basis of similar distribution, appear to be more or less contemporaneous occur as separate minerals, although the two may commonly be seen in the same field of view on one polished section.

A similar paradox has been noted in the occurrence of gold and silver precipitated from the cyanide solution in the milling process. Gold and silver, both carried in solution in the cyanide, are precipitated as the separate metals and not as the gold-silver alloy.

Similarly in the supergene zones of other Nevada precious metal deposits, gold and silver occur as separate minerals. Thus, gold solutions, whether naturally occurring in the earth or artificially in a cyanide tank, apparently are unable to form a gold-silver alloy. But in most epithermal gold deposits in Nevada, electrum is present. It is possible that with decreasing temperature of solution, the tendency for the formation of electrum decreases. If this is so, the temperature of ore solutions in the Getchell deposit must have been lower than those of other precious metal deposits of Nevada.

Elsewhere in the world, hypogene native silver is found in four main types of deposits: (a) associated with sulfides, silver minerals zeolites, barite, fluorite, and quartz (Kongsberg, Norway); (b) occurring with nickel and cobalt sulfides and arsenides in a calcite gangue (Cobalt, Ontario); (c) with uraninite and nickel-cobalt minerals (Great Bear Lake); and (d) with native copper and zeolites (Keweenaw Peninsula) (24, p. 98). No description of hypogene silver in minor amounts in any other deposit dominantly of gold has been found by the writer.

GENESIS.

Sequence of Deposition.

Ore deposition is a gradational process. It is not one in which the widespread deposition of one mineral stops before another mineral begins to be deposited. Any mineral will be deposited when the physico-chemical conditions are such as to make its constituents unstable in solution. It would be folly to assume that, at any one time during deposition, similar conditions existed throughout the entire area of mineralization. So a mineral that was deposited late in the sequence in one place may actually be earlier than a mineral deposited early in the sequence in another spot. Any discussion of exact sequence, therefore, must be limited to a small locality within the ore body, where similar physico-chemical conditions existed at any given time.

In general, the sequence of deposition (graphically presented in Fig. 29) of what is now the economic ore at Getchell, was as follows. Early, low-intensity solutions, being dilute, were able to do no more than locally rework the rock constituents and introduce small quantities of pyrite carrying minor gold. Coarse-grained quartz and calcite and small amounts of pyrite are the early minerals. Somewhat later, fine-grained quartz and carbon, probably derived from underlying rocks, were introduced, and were followed by the major sulfides, pyrite, pyrrhotite, arsenopyrite, and chalcopyrite. In the still later, economically important stage, marcasite, realgar, orpiment, stibnite, magnetite, gold, and silver were deposited. The period of deposition of each mineral overlapped those of several others, so these minerals may be considered as more or less contemporaneous. In any one place in the ore body, gangue minerals derived from the nearby and underlying rocks were deposited early in the sequence and metallic minerals foreign to the country rock were mainly deposited somewhat later. Most of the gold, together with silver and magnetite, is apparently the latest of the metallic minerals deposited.

In the outlying, submarginal portions of the ore body, the sequence was apparently similar to that in the now economic sections, except that the later marcasite-realgar-gold period did not appear there. Deposition in these fringing areas of the main ore body may be considered as being more or less contemporaneous with the economically important phase of deposition in the central channelways. The early, gold-poor stage of deposition in these channelways preceded any deposition in the outlying areas.

The distribution of *economic* amounts of gold is quite similar to that of realgar. There are apparently two modes of occurrence of visible gold: (1) it is sparsely distributed throughout the ore bodies, in gumbo, argillite, and limestone alike. This form of gold was deposited early in the period of formation of the realgar and these widely scattered gold particles occur in all ore that contains realgar, although they rarely occur within realgar grains. Gold of this stage probably began its growth by adsorption on carbon, porous pyrite, and in realgar only where favorable conditions existed. Silver and the rare electrum were probably more or less contemporaneous with this earlier, low-grade phase of gold mineralization as they have the same general distribution. The precious

metals deposited at this time are not to be confused with the non-commercial amounts of gold believed to be in solid solution in the earliest pyrite. To the contrary, gold of this period constitutes most of the gold in the ore bodies except the extremely local and rich shoots. (Gold of this period is illustrated in Figs. 18, 19, 20, 21.)

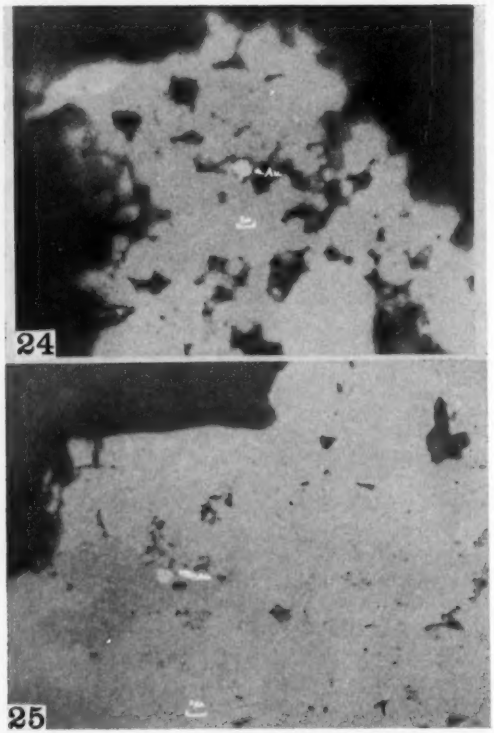


FIG. 24. Photomicrograph of polished section of pyritic concentrate, heated to 600° C, showing gold inclusion in pyrite-marcasite intergrowth. Finely dispersed gold was apparently driven to the opening in the pyrite by the heating. Note the difference in reflectivity between gold and pyrite. × 2,875.

FIG. 25. Photomicrograph of polished section of pyritic ore. The small gold grain occurs in a porous section of the pyrite-marcasite intergrowth. × 2,875.

(2) Toward the end of the period of deposition of marcasite and realgar, the most intense ore solutions passed through the few most permeable channels in the ore body which lay within the zones of abundant gumbo. A marked change in conditions of deposition must have occurred to allow the formation

of extremely rich, though small, lenses of gold and magnetite (Figs. 22, 23). Minute amounts of carbon were deposited at this time, rimming occasional particles of gold.

Summary of Sequence.—The changes in the nature of deposition with time were brought about largely by changing conditions of deposition. The changes were gradational and the minerals characteristic of the early stage were being deposited in the outlying areas at the same time that the late stage minerals were forming in the ore shoots. At the earliest stage of deposition at the known depth horizon, pyrite containing low-grade gold was deposited, with some quartz, calcite, sericite, and chlorite, near the major channelways. As the flow of hot solutions continued, more and more heat was carried into the zones of mineralization, the intensity-character increased, pyrite and lean gold were deposited farther and farther out, whereas the minerals from solutions of higher intensity were deposited toward the centers of mineralization by replacement or re-solution of those minerals that had been stable during the earlier and feebler stages then and there existing. Realgar, marcasite, and the economically important gold, which latter was becoming richer with time, were deposited in the main channelways at about the same time that the solutions in the outlying portions of the veins and wall rock were depositing disseminated pyrite and included submicroscopic gold in non-commercial amounts.

Nature of the Hydrothermal Fluid.

The hydrothermal fluid contained water, arsenic, iron, and sulfur, with minor amounts of copper, gold, silver, molybdenum, mercury, barium, and fluorine. It also contained silica, lime, and carbon, which were probably largely of local derivation. This fluid was hot, probably at a temperature of between one and two hundred degrees Centigrade. At depth it was probably alkaline, although there is no direct evidence of this. The underlying rocks contain far greater quantities of alkaline than acid elements, so, even if the solution were thought to have been acid on leaving its source, it presumably would soon become alkaline.

Transportation of Gold.—Soluble compounds of gold are not abundant. In the past, emphasis has been placed on auric chloride as the form in which gold is transported (21). However, chlorides, if present at all, are rare constituents of an ore body, especially as compared to sulfides; and even though most chlorine compounds are highly soluble and would not be precipitated, there is rarely, in any district, tangible indication that chlorine in whatever state of combination has passed through the channelways in the quantities required if the metals were brought to the place of deposition as chlorides. It seems far more reasonable to assume that the gold is transported as a soluble sulfide. Smith (27) suggested that gold may be dissolved in alkali sulfide solutions with the formation of alkali thioaurites, the general formula for which is $2Na_2S \cdot Au_2S$.

Gold is far more soluble in alkali sulfide solutions than are most metals. It belongs in the group of metals whose sulfides are highly soluble in dilute aqueous solutions of alkali sulfides at room temperature. With gold in this

group are mercury, bismuth, antimony, arsenic, and tellurium. Silver is the most soluble of the group of metals whose sulfides are soluble in aqueous solutions of alkali sulfides at high temperatures. This may explain the close spatial relation between realgar, gold, and silver, at the Getchell mine. It may also help to explain the sequence there shown, in which cinnabar, stibnite, realgar, gold, and silver are present as late minerals.

The question of transportation of gold, however, cannot yet be regarded as settled with finality, and must hopefully wait for additional experimentation and ideas. But several considerations make the thesis of transportation as double sulfides or sulfide complexes worthy of consideration for the case at Getchell.

Precipitation of Gold.—Alkali sulfides easily form double salts with certain metallic sulfides. If the sulfide concentration of sodium thio-metallic salts is lowered sufficiently, simple metal sulfides are precipitated. For gold, a reduction in sulfide content in solution causes separation as the metal rather than as sulfide, since gold sulfide is unstable at temperatures greater than 40° C (27).

If such a process may account for the deposition of minerals in the Getchell deposit, then there should be some evidence of decreasing sulfide ion content in solution. Orpiment, with a high sulfur content, is earlier than realgar, which contains less sulfur. This may be an indication of decreasing sulfide concentration. Pyrrhotite, pyrite, and marcasite are early and magnetite appears to be late. Laboratory experiments were carried out by the writer in which various forms of iron sulfides were synthesized from solutions at temperatures of from 400° to 600° C. The results indicate that with an excess of sulfide ions, pyrite and marcasite are formed and that with a decrease in sulfide concentration pyrite disappears and pyrrhotite is deposited. With a further decrease in sulfur, pyrrhotite, magnetite, and hematite are formed. This shift from the disulfides through the near-monosulfides to the oxides with a decrease in sulfide ion concentration is thus entirely compatible with the observed sequence at Getchell and suggests a similar decrease in sulfide concentration in the solutions as mineral deposition proceeded.

Changes in Character of Solutions During Deposition.—The presence of early calcite and pyrite and later marcasite and such sulfates as barite and possibly gypsum suggests a gradual change from alkaline to neutral and finally to acid solutions. The presence of marcasite especially indicates a change to acid solutions (1). This gradual change is not uncommon in near-surface deposits and is particularly common in fumaroles or hot springs. It essentially represents a change of sulfide to sulfate ion. This may be explained by Allen's reaction, in which free sulfur reacts with water at certain temperatures to form the sulfide ion and sulfate radical, as follows: $4S + 4H_2O = 3H_2S + H_2SO_4$. If H_2S is removed from the system, the reaction will move toward the right, bringing about a concentration of sulfuric acid which may convert the initially alkaline solution to acid.

On entering into shattered, permeable rock such as the Getchell fault zone, the ore solutions undergo loss of pressure which facilitates the loss of a gas

phase, such as H_2S, from the liquid phase. With this selective evaporation, the sulfur content of the remaining solutions will decrease as they change from alkaline to acid composition. With decreasing sulfur content and accompanying acidification, pyrite will alter to marcasite, realgar will be formed in place of orpiment, and gold will be precipitated. With further decrease in sulfur, the iron sulfides will cease depositing and magnetite will begin to form. In those environments where sulfuric acid is abundantly developed, hypogene sulfate minerals may be deposited.

If such a process has taken place at Getchell, one might question why marcasite and realgar are restricted to certain zones or shoots within the veins. This is believed related to the possibility that the hydrothermal solutions did not pass through all portions of the veins at equal rates, with the consequences discussed below. The ore-carrying solutions were probably somewhat hotter

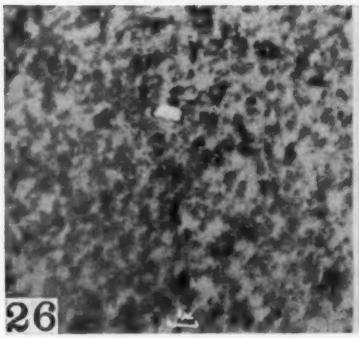


FIG. 26. Photomicrograph of polished section of pyrite. The extreme porosity was not noted under lower magnification. Some black openings are filled with quartz; many are vacant. The white grain in the center is gold. × 4,000.

FIG. 27. Photomicrograph of polished section of gold-rich activated charcoal used in the recovery of the gold in the milling process. White grain is gold, on rim of a charcoal cell. This charcoal is used because of its high adsorptive power. Compare porosity and surface to that of the pyrite in Figure 26.

than the wall rock and, during part of the period of mineralization at least, were actually heating the rocks through which they passed. As the rock became hotter the solutions could lose an increasingly small proportion of their heat. Thus, at any one point in the vein, the temperatures of the wall rock and of the passing solutions were rising and the geothermal gradient was there becoming steeper. This increase in temperature was not uniform throughout the veins, but was more marked in the loci of greater permeability through which greater volumes of the heat-carrying solutions passed. This process must not be misinterpreted to mean that any given portion of the moving solution was actually becoming hotter with time; it was simply cooling at an increasingly small rate, and therefore was followed by portions of solutions progressively hotter.

So within the veins there were hot, permeable loci separated by less permeable and cooler places. The separation from the solution of H_2S in the gas phase would be favored by a sufficiently high temperature to keep up its production by the Allen reaction cited above, and by a pressure so low as not to retain

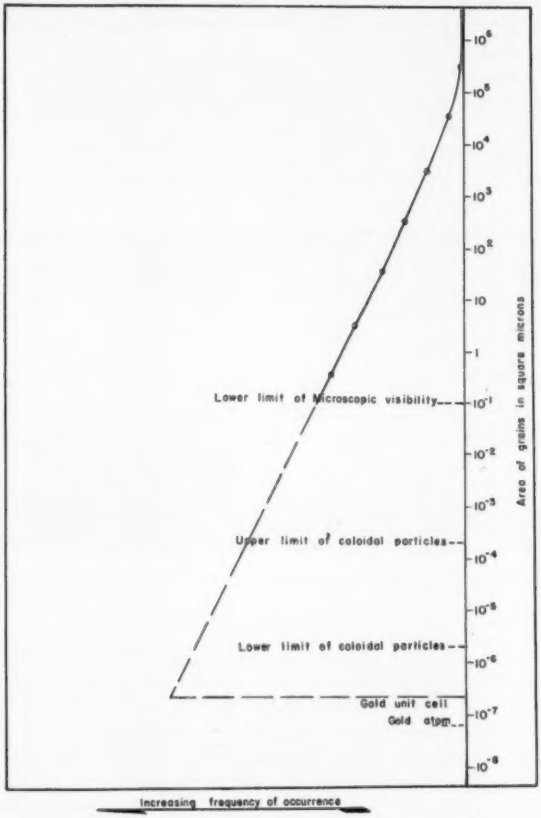

Lower limit of microscopic visibility
Upper limit of colloidal particles
Lower limit of colloidal particles
Gold unit cell
Gold atom
Area of grains in square microns
Increasing frequency of occurrence

FIG. 28. Frequency distribution of gold grains, showing probable extension in submicroscopic range. A logarithmic scale is used on the abcissa.

the H_2S in solution. Such rather special combination of temperature and pressure would be most probably along the more permeable and hence hotter axes of flow.

Thus the ore solutions probably remained alkaline in the less permeable portions of the veins while they were becoming neutral or somewhat acid in

the hotter ore shoots. Pyrite was deposited throughout the veins in the earliest, alkaline period of deposition, and only in the lower-grade, less permeable and cooler sections during later stages of mineralization. Realgar, marcasite, and the richer occurrences of gold were restricted to the hotter parts of the veins where the solutions were neutral or acid. The gold, realgar, and magnetite were deposited from hotter solutions than those that formed the pyrite and the conventional gangue minerals.

In the past there has been a tendency on the part of geologists to assume that the terms "low-temperature mineral" and "late mineral" are synonymous. Graton (11) has questioned the validity of this reasoning, and recent work at Butte has indicated that late minerals were actually formed at higher temperature and under conditions of higher intensity than the early minerals (26).

Further evidence in support of such relations of temperature and sequence is found in the Getchell deposit. The early solutions were apparently dilute and undersaturated with the ore minerals. These solutions were able only to redistribute the rock minerals within their respective beds because they were already considerably depleted in intensity, and could only transport dissolved material a few inches. Those portions of the later solutions that were able to remain within the more permeable loci in the veins, benefitting by the heating already accomplished there, were able to do a more "intense" kind of work. Gangue minerals in these favored portions were no longer so localized, and quartz replaced limestone, argillite, and andesite with about equal ease. In place of the early, coarse-grained quartz that was deposited in a leisurely manner from dilute, alkaline solutions, the fine-grained quartz was formed by more rapid growth from relatively concentrated and probably acid solutions. The earlier, euhedral pyrite gave way to the later, irregular pyrite-marcasite intergrowths that probably represent deposition from more concentrated and hence more intense solutions.

Age of Mineralization.

The Getchell ores were deposited at some time subsequent to the intrusion of the andesite porphyry, which is tentatively dated as early or middle Tertiary. A period of silicification to form the opalite occurred after deposition of the rhyolite tuff. The strongest mineralization in the Getchell ore bodies occurs toward the north end of the mineralized zone nearest to the deep pipe of rhyolite tuff. It is possible that the ores are later than the rhyolite and represent a late phase of that period of igneous activity.

The Getchell ore body is similar in many ways to the gold-realgar deposits at Manhattan, Nevada, about 150 miles to the south. At Manhattan, both early andesite and late rhyolite dikes occur near the ore body. In the description of this deposit, Ferguson (8) suggests that the gold mineralization may be post-rhyolite. He points out that at Round Mountain, 50 miles north of Manhattan, gold ore containing realgar occurs in a rhyolite plug and is therefore later than the rhyolite (7), and that these two deposits may belong to a post-rhyolite period of mineralization. The close parallelism in the character

of the Getchell and Manhattan deposits suggests that they may belong to the same general period of mineralization.

In his description of the mining camps of Nevada, Ferguson (9) shows that the Tertiary precious metal deposits in that area may be divided into two groups of widely differing character. In the older group the deposits are generally more persistent laterally and vertically. They all contain manganiferous calcite and have a ratio of silver to gold greater than 1:1. In the other group, gold is generally present in larger amounts than silver and the structures are less persistent. Goldfield, type example of this group, has a gold-silver ratio of 7:3.

Realgar is not found in most of the gold-rich deposits. In those in which it is found, Getchell and Manhattan, the bullion reports indicate the great preponderance of gold over silver, the gold-silver ratio varying from 10:1 at Getchell to 17:1 at Manhattan. It is possible that this type of ore deposit, characterized by a very high gold-silver ratio and the presence of realgar, may represent a third, still later group of deposits formed in late Pliocene or early Pleistocene time. These deposits have many features in common that are not shared by other late Tertiary gold ores. Both contain realgar, orpiment, cinnabar, carbon, stibnite, fluorite, and pyrite. An unusual green calcite is found in each. Silver sulfides or sulfosalts are lacking. At both deposits the gold is very fine-grained and is closely related spatially to realgar and carbon. In each, lead, zinc, and copper sulfides are rare or nonexistent. Both contain relatively large replacement bodies that are more important than the single narrow fissure veins.

Ferguson (8, p. 106) suggests that the high gold-silver ratio may be due to the presence of arsenic minerals. He proposes the theory that hypogene solutions rich in arsenic and free from lead, zinc, and copper tend to precipitate gold without any important mixture of silver. There appears to be no chemical basis for such a reaction and the common occurrence of gold-poor proustite deposits would seem to disprove this theory. Butler (5) gave a more plausible explanation, suggesting that the presence of carbon may be important in bringing about a high gold-silver ratio, as carbon is known to precipitate gold selectively from a gold-silver solution. Carbon is undoubtedly important in precipitating larger amounts of gold, but there may be a simpler explanation of the high gold-silver ratio.

Hydrothermal solutions, on rising, may be expected to change gradually from alkaline to some degree of acidity. As a consequence, gold will tend to be deposited as soon as sufficient sulfide ions are removed, but silver sulfides and sulfosalts, being soluble in acid solutions, will no longer be deposited but will be swept along the channelways. The sulfuric acid will gradually be lessened in the course of this journey, partly through the precipitation of sulfates and partly by reaction with sericite and feldspars to form clay minerals. When and where the acidity becomes sufficiently lowered, the silver-sulfur compounds could again be precipitated to form a shallow silver zone capping the gold.

It is possible that the solutions might reach the surface before adequate reduction of the acid had occurred. In such a case, the resultant deposit

would consist only of a gold zone. Getchell, Manhattan, and Goldfield may be examples.

There are gradations in the character of the deposits of from middle to late Tertiary age (i.e. Tonopah, Goldfield, Manhattan, Getchell) and it is probable that the entire late Tertiary period was an epoch of continual mineralization.

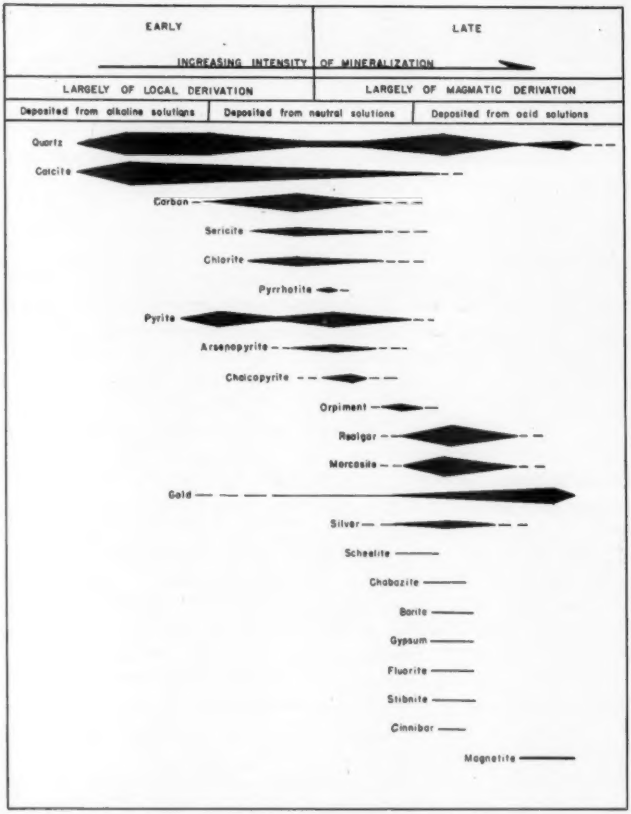


FIG. 29. Sequence of deposition of Getchell ore minerals.

The changes in character of these deposits may be explained by the fact that decreasing age has permitted an increasing escape from erosive removal of the shallowest portions of the initial deposits.

The similarities between the Getchell and Manhattan deposits have been discussed previously. There are, however, certain discrepancies between the

two deposits. The presence of adularia in some mines at Manhattan suggests that it may represent a slightly more intense phase of mineralization. Native silver as a hypogene mineral is not reported from Manhattan and, if the presence of native silver together with native gold is an indication of lower intensity, the lack of silver at Manhattan corroborates the other evidence favoring higher intensity for that camp.

A feature of the Getchell deposit that sets it apart from the typical epithermal gold deposits is the nearly complete lack of certain common epithermal structures such as "colloform" banding, crustification, and comb structure. This suggests that the Getchell deposit may be intermediate in character between the typical epithermal precious metal and the quicksilver deposits. Many of the quicksilver veins of Nevada show a close relationship to both the gold-silver and stibnite-realgar types of deposits (20, p. 473). The deposits at Steamboat Hot Springs, located a few miles south of Reno, contain some cinnabar and show many striking similarities to the Getchell deposit. At Steamboat as well as Getchell, Tertiary igneous activity is represented by early andesite and late pumiceous rhyolite. The rhyolite at Steamboat is Pleistocene or recent, a fact that may suggest a Quaternary age for the Getchell rhyolite tuff. Silica in the form of opal, chalcedony, and fine-grained quartz is abundant in each deposit. According to Brannock et al (4) the Steamboat waters contain a mud which is largely composed of tiny particles of opal or a silica gel. This mud apparently closely resembles the Getchell gumbo, and its other features strengthen the resemblance. Minute acicular crystals of stibnite occur in the mud and have also been found floating as a thin scum on the surface of the waters of the spring. These fine-grained aggregates of stibnite needles closely resemble the unusual felt-like stibnite crystals from the Getchell ore body. Pyrite and realgar have been identified in the Steamboat mud, and the presence of an iron oxide, possibly magnetite, is suggested. The most striking feature common to the mud and the gumbo is the presence of gold. Two of the most important wells at Steamboat contained mud with between 0.3 and 0.4 ounces of gold per ton. The ratio of gold to silver in these muds is 1 :3. Copper is present in the muds, as in the Getchell gumbo, in extremely small amounts.

The siliceous sinter at Steamboat contains pyrite, arsenopyrite, stibnite, and some cinnabar. The sinter is stained in places with a red-brown antimony ochre, metastibnite; ilsemannite has also been found.

These features strongly suggest a very close genetic relation between Getchell and Steamboat Springs.

Figure 30 shows the location of the major deposits of Nevada in which either cinnabar or gold is the economic mineral. The important cinnabar deposits lie in a relatively narrow, northerly trending belt that cuts the west-central part of the state. The chief gold deposits, on the other hand, show no regularity of distribution, but are widely spaced throughout the entire state.

The Great Basin is composed of a series of northerly-trending structures, both folds and faults. Even the recent faults (10) trend in a northerly direction. Most of the cinnabar deposits are relatively young, and all are probably Pliocene or later. It is possible that a major late Tertiary belt of faulting is

now marked by the larger cinnabar deposits shown in Figure 30. Such a belt would act as a locus for the cinnabar-depositing solutions.

Nolan (23, p. 152) has described a geanticline that divided the Paleozoic geosyncline, persisting from late Devonian to early Permian time. The axis of this geanticline is shown in Figure 30. It may be merely coincidence that most of the larger cinnabar deposits and the Getchell ore bodies lie along or near this axis, as the period of geanticlinal deformation was over by Permian

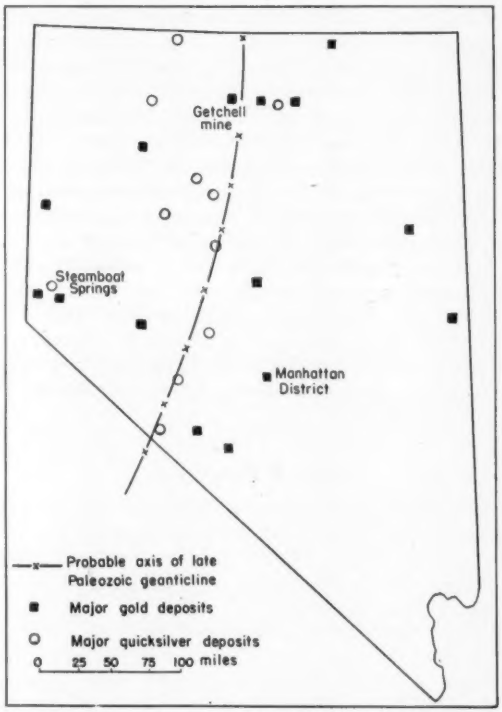


FIGURE 30 MAP OF NEVADA SHOWING LOCATION OF MAJOR GOLD AND QUICKSILVER DEPOSITS

time whereas the gold and cinnabar deposition was late Tertiary or early Quaternary. It is nevertheless possible that the geanticlinal axis was and has continued to be a zone of weakness along which later, deep-seated faults have formed from time to time. Along such faults, mineralizing solutions could rise to deposit cinnabar or gold.

The Getchell mine is located within this cinnabar belt, near its eastern margin. The Manhattan deposits lie slightly east of this belt. It may again be

coincidence that these two gold occurrences lie near or within the belt, but their mineralogic and textural features suggest a genetic relation to cinnabar deposits. It is probable that the Getchell and Manhattan gold deposits represent a gradation between the earlier gold ores such as Goldfield and the more recent cinnabar deposits.

A period of mineralization may thus be considered to have begun in middle Tertiary time with the deposition of silver-gold ore bodies, gradually changing in character to form the deposits in which gold slightly exceeded silver. Somewhat later the arsenical Getchell-Manhattan type was formed, with gold far outweighing silver, and with cinnabar present in small amounts. The Getchell and Manhattan deposits apparently may be regarded as a link toward bridging the gap between the precious metal and the mercury deposits. In the latest important stage of this period of mineralization, the cinnabar ore bodies were formed. The final dying stage of mineralization is represented by Recent hot spring deposits. Many of these are similar in character to the cinnabar deposits, but a few, such as the Golconda tungsten-manganese blanket (17), are completely different. The hot spring deposits presumably represent a less intense phase of the same period of mineralization that formed the cinnabar vein merely because the former are shallower. The variation in intensity would include changes in temperature, pressure, and particularly in concentration. Regarding the possibility of a protracted epoch of Tertiary mineralization, Lindgren said, "This whole process of metallization, beginning at the earliest Cretaceous, closing at the end of the Tertiary, and feebly continuing today, is actually one continuous operation of separation of volatile constituents from the magma . . ." (19, p. 179).

Depth of Formation.

The Getchell ore bodies were formed under a relatively shallow cover. The large vugs in the ore and the intensely shattered nature of the ore zone are the best evidence favoring deposition in a shallow environment. The plastic, unconsolidated character of the gumbo likewise suggests a near-surface origin. As relatively thin outliers of rhyolite tuff still remain near the ore zone, it is probable that erosion has not removed more than a few hundred feet of rock since the deposition of the rhyolite.

The apparently close affiliation between the Getchell mineralization and the cinnabar deposits suggests that they were formed under somewhat similar conditions. Bailey stated that the opalite type of cinnabar deposit was probably formed at depth of about 500 feet beneath the surface (3, p. 20). The present tops of the Getchell ore bodies were probably deposited within a thousand feet of the then-existing surface.

Genetic Classification.

The Getchell ore bodies are clearly epithermal as outlined by Lindgren (20). They constitute a particular and self-characteristic example, a narrow subdivision of the broader epithermal class. The Getchell deposit belongs

among those that represent the least intense portion of the epithermal class. Graton, in proposing the telethermal depth-zone (11, pp. 547–551), has suggested that the epithermal deposits do not represent the very lowest intensity end members of the hydrothermal family. He points out that certain low-intensity stibnite-realgar and cinnabar deposits may be a gradational form between typical epithermal deposits that are characterized by relatively rapid deposition and telescoping because of steep thermal gradients, and still feebler telethermal deposits formed by leisurely deposition in a cooler environment.

Despite its many unusual features, the Getchell deposit must be considered as epithermal on the basis of the telescoped nature of mineralization. It has been suggested that this deposit may represent a gradation between the typical epithermal precious metal and the cinnabar deposit. The increasing differences from the progressively older and somewhat deeper-lying precious metal deposits and the growing evidences of similarity with the cinnabar deposits progressively closer to Getchell in youth and shallowness, place the Getchell deposit close to the feeblest end of the epithermal group. It may well be that hot-spring sinters were formed at the surface only a few hundred feet above the present vein outcrops.

PARK CITY, UTAH,
Nov. 3, 1950.

BIBLIOGRAPHY.

1. Allen, E. T., Crenshaw, J. L., and Merwin, H. E., Effect of temperature and acidity in formation of marcasite and wurtzite; a contribution to the genesis of unstable forms: Am. Jour. Sci., 4th Ser., vol. 38, pp. 393–431, 1914.
2. Auger, P. E., Zoning and district variations of the minor elements in pyrite of Canadian gold deposits: ECON. GEOL., vol. 36, pp. 401–423, 1941.
3. Bailey, E. H., and Phoenix, D. A., Quicksilver deposits in Nevada: Nevada Univ. Bull., vol. 38, no. 5, 1944.
4. Brannock, W. W., Fix, P. F., Gianella, V. P., and White, D. E., Preliminary geochemical results at Steamboat Springs, Nevada: Am. Geophys. Union Trans., vol. 29, no. 2, 1948.
5. Butler, B. S., Loughlin, G. F., and Keikes, V. C., The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, pp. 391–395, 1920.
6. Edwards, A. B., Textures of the Ore Minerals, Australasian Inst. Min. Metallurgy, Melbourne, 1947.
7. Ferguson, H. G., The Round Mountain district, Nevada: U. S. Geol. Survey Bull. 725, pp. 383–406, 1921.
8. Ferguson, H. G., Geology and ore deposits of the Manhattan district, Nevada: U. S. Geol. Survey Bull. 723, 1924.
9. Ferguson, H. G., The mining districts of Nevada: ECON. GEOL., vol. 24, pp. 115–148, 1929.
10. Gianella, V. P., The earthquake of December 20, 1932, at Cedar Mountain, Nevada, and its bearing on the genesis of Basin Range structure: Jour. Geology, vol. 42, pp. 1–22, 1934.
11. Graton, L. C., The depth zones in ore deposition: ECON. GEOL., vol. 28, pp. 513–555, 1933.
12. Graton, L. C., Personal communication, 1950.
13. Gross, J., and Scott, J. W., Precipitation of gold and silver from cyanide solution on charcoal: U. S. Bur. Mines, T. P. 378, 1927.
14. Haycock, M. H., The role of the microscope in the study of gold ores: Canadian Inst. Min. Metallurgy, vol. 40, pp. 405–414, 1937.
15. Head, R. E., Form and occurrence of gold in pyrite from a metallurgical standpoint—Coated gold: U. S. Bur. Mines, Rept. Inv. 3275, pp. 39–46, 1935.
16. Hobbs, S. W., Geology of the northern part of the Osgood Mountains, Humboldt County, Nevada, Ph.D. Thesis, Sterling Library, Yale University, 1948.
17. Kerr, P. F., Tungsten-bearing manganese deposits at Golconda: Geol. Soc. America Bull., vol. 51, pp. 1359–1390, 1940.
18. Kuranti, G., Synthetic study of gold-containing pyrite: Suiyokwai-Si, vol. 10, pp. 419–424, 1941 (abstracted in Chem. Abstracts, vol. 35, p. 3563, 1941).

19. Lindgren, W., Differentiation and ore deposition in the Cordilleran Region *in* Ore Deposits of the Western States, pp. 152–180, Am. Inst. Min. Met. Eng., New York, 1933.
20. Lindgren, W., Mineral Deposits, McGraw-Hill Book Co., New York, 1933.
21. Lindgren, W., Succession of minerals and temperatures of formation in ore deposits of magmatic affiliation: Am. Inst. Min. Met. Eng. Trans., vol. 126, pp. 356–375, 1937.
22. Maslenitsky, I., On some cases of formation of disperse gold segregations in iron sulfides: Acad. sci. U.R.S.S. Comptes rendus (Doklady), vol. 45, no. 9, pp. 385–388, 1944.
23. Nolan, T. B., The Basin and Range Province in Utah, Nevada, and California: U. S. Geol. Survey Prof. Paper 197-D, 1943.
24. Palache, C., Berman, H., and Frondel, C., The system of mineralogy of James Dwight Dana and Edward Salisbury Dana, Yale University 1837–1892, 7th ed., John Wiley & Sons, New York, 1944.
25. Pauling, L., The Nature of the Chemical Bond, 1939.
26. Sales, R. H., and Meyer, C., Wall rock alteration at Butte, Montana: Am. Inst. Min. Met. Eng., Tech. Pub. 2400, 1948.
27. Smith, F. G., The alkali sulfide theory of gold deposition: ECON. GEOL., vol. 38, pp. 561–589, 1943.
28. Stillwell, F. L., and Edwards, A. B., An occurrence of sub-microscopic gold in the Dolphin East Lode, Fiji: Australasian Inst. Min. Metallurgy, vol. 141, pp. 31–46, 1946.
29. Van Aubel, R., Sur l'importance dans les minerais d'or du calibre des particules: Annales des mines, 13e série, Tome 16, pp. 155–161, Livraison de 1939.

NATURAL POZZOLANS FOR CONCRETE.

RICHARD C. MIELENZ, KENNETH T. GREENE,
AND N. CYRIL SCHIELTZ.

CONTENTS.

	PAGE
Abstract	311
Introduction	311
Use of pozzolans	312
Mineralogic composition and properties of pozzolans	313
Pozzolanic activity	313
Activity type	315
Activity Type 1	319
Activity Type 2	321
Activity Type 3	322
Activity Type 4	323
Activity Type 5	323
Activity Type 6	323
Geologic occurrence of natural pozzolans	323
Conclusions	327
Acknowledgments	328

ABSTRACT.

Many geologic formations in the United States yield pozzolans or materials which can be converted into pozzolans by grinding and calcination. When properly selected, processed, and used, pozzolans will reduce costs, improve quality of concrete, protect concrete against effects of reaction between aggregate and cement alkalies, and inhibit attack by aggressive waters. With improved knowledge of their properties and sources, use of pozzolans is increasing. The geologist and petrographer can aid materially in the search for and exploitation of deposits, and in selection of processing methods.

Natural pozzolans owe their activity to five substances, namely: volcanic glass, opal, clays, zeolites, and hydrated aluminum oxides. Each active substance contributes characteristic properties to the pozzolan; consequently, the quality of proposed materials and need for special processing usually can be predicted from petrographic analyses.

Geologic formations known to yield pozzolans are indicated, and data on 95 samples representative of tested formations are summarized. Properties and response to heat treatment of pozzolans of the various activity types are discussed.

INTRODUCTION.

POZZOLANS [1] are natural or artificial siliceous and aluminous substances which are not cementitious themselves but which react with lime in the presence of water at atmospheric temperatures to produce cementitious compounds. These

[1] Many variations in spelling of the word are to be found in the literature, the commonest being "pozzolana." The spelling used here is that recommended by the Bureau of Reclamation, United States Department of the Interior, and the Portland Cement Association.

materials are used to advantage as a portland cement admixture or as a partial replacement of the portland cement ordinarily used in manufacture of mortar or concrete. Use of pozzolans in concrete construction is increasing; moreover, it is anticipated that their importance will grow more rapidly as sources of suitable materials are discovered and means of beneficiation are developed. Geological materials of several types produce economical pozzolans of satisfactory or excellent quality. This paper indicates the materials which can be used as sources of pozzolan and summarizes the properties characteristic of each.

The data on which this paper is based were derived largely from investigations under way in the Denver laboratories of the Bureau of Reclamation since 1933.

USE OF POZZOLANS.

Cements have been used in construction for several thousand years, first in mortar for masonry and much later in concrete. Originally, as in ancient Egypt, cement was produced by calcination of gypsum; but during the Greek and Roman periods, calcined limestone was employed either alone with water or mixed with sand and gravel or crushed stone, tile, or brick. With experience, the ancient engineers observed that some aggregate materials produced mortar and concrete which were stronger and more durable and which hardened as well under water as in air. These aggregates were volcanic ashes and tuffs. They included Santorin earth, a rhyolite tuff from the island of Santorin, and the phonolitic tuffs in the vicinity of Vesuvius, particularly from deposits near the town of Pozzuoli, from which locality these materials derive their name: pozzolan.[2]

With penetration of the Romans into western Europe, similar volcanic ashes and tuffs were found and used in southeastern France and subsequently along the Rhine River between Cologne and Coblenz. The Romans discovered too that ground tile, pottery, and brick would serve as a pozzolan; materials of this type were used widely where volcanic pozzolans were unavailable, as in England. Similar use of finely ground brick is made today in India and Egypt.[3]

Following development of natural cement, a hydraulic cement produced by burning of argillaceous limestone, during the late eighteenth century, and particularly with introduction of portland cement during the early part of the nineteenth century, use of pozzolanic cements declined greatly. However, it has been known for more than 60 years that several desirable properties could be derived by admixture of a suitable pozzolan with portland cement. Experience has shown that the optimum proportion of pozzolan usually falls between 10 and 30 percent by weight of the portland cement. Portland-pozzolan cements ordinarily cost less; heat of hydration is lower and the maximum rate of

[2] Lea, F. M., and Desch, C. H., The chemistry of cement and concrete, p. 429, Longmans, Green and Company, New York, 1935. Bogue, R. H., The chemistry of portland cement, p. 572, Reinhold Publishing Corporation, New York, 1947.

[3] Lea, F. M., and Desch, C. H., op. cit.

heat development is reached at an earlier age; grindability is improved; plasticity of the fresh concrete is increased; and segregation of the constituents of the concrete and bleeding of water are decreased. In addition, permeability of the concrete characteristically is decreased; resistance to attack by sulfate-bearing water is increased; and tensile strength typically is improved. More recently, use of certain pozzolanic admixtures has been found to eliminate, or at least greatly retard, progress of the reaction between cement alkalies and aggregates.[4]

Unfortunately, several deficiencies in the quality of concrete may be introduced if inferior pozzolans are used or if excessive replacement of portland cement is attempted. The rate of hardening and development of compressive strength and elasticity of the concrete can be retarded seriously; shrinkage due to drying might be increased; and resistance to freezing and thawing might be reduced. Moreover, some otherwise suitable pozzolans have been found to increase deterioration resulting from the alkali-aggregate reaction.

Portland-pozzolan cements, particularly for marine construction, have been used widely in Germany, France, Italy, Russia, and Japan. In the United States, portland-pozzolan cements were used in the construction of several large engineering works in the West, such as the Los Angeles Aqueduct, San Francisco Bay Bridge, Golden Gate Bridge, and Friant Dam, California; Bonneville Dam, Washington-Oregon; Altus Dam, Oklahoma; Davis Dam, Nevada-Arizona; and Hungry Horse and Canyon Ferry Dams, Montana. Increased use of portland-pozzolan cements in general construction practice is envisioned as the result of research being conducted by Governmental agencies, universities, and private companies.

MINERALOGIC COMPOSITION AND PROPERTIES OF POZZOLANS.

Pozzolanic Activity.—The mechanism by which pozzolans accomplish changes in the properties of concrete is not known fully.[5] However, it can be demonstrated that the action of pozzolans is in part physical and in part chemical. The physical effects relate particularly to specific gravity, particle shape, fineness, and water-absorbing capacity. The specific gravity of most pozzolans is low (ranging generally from 2.3 to 2.8, in contrast to about 3.1 for portland cement), as a result of which the pozzolan occupies a greater volume than the weight-equivalent of portland cement. Thus, if the cement-to-aggregate ratio by weight is held constant, use of a portland-pozzolan cement effectively increases the volume of cement in the concrete, with resulting tendency to increased workability, plasticity, and water requirement.

[4] Stanton, T. E., Porter, O. J., Meder, L. C., and Nicol, A., California experience with expansion of concrete through reaction between cement and aggregate: Am. Concrete Inst. Proc., vol. 38, pp. 209–236, 1942. Hanna, W. C., Unfavorable chemical reactions of aggregates in concrete and a suggested corrective: American Society for Testing Materials Proc., vol. 47, pp. 986–999, 1947.

[5] Lea, F. M., The chemistry of pozzolanas: Symposium on the Chemistry of Cements Proc., pp. 460–490, Stockholm, Sweden, 1938.

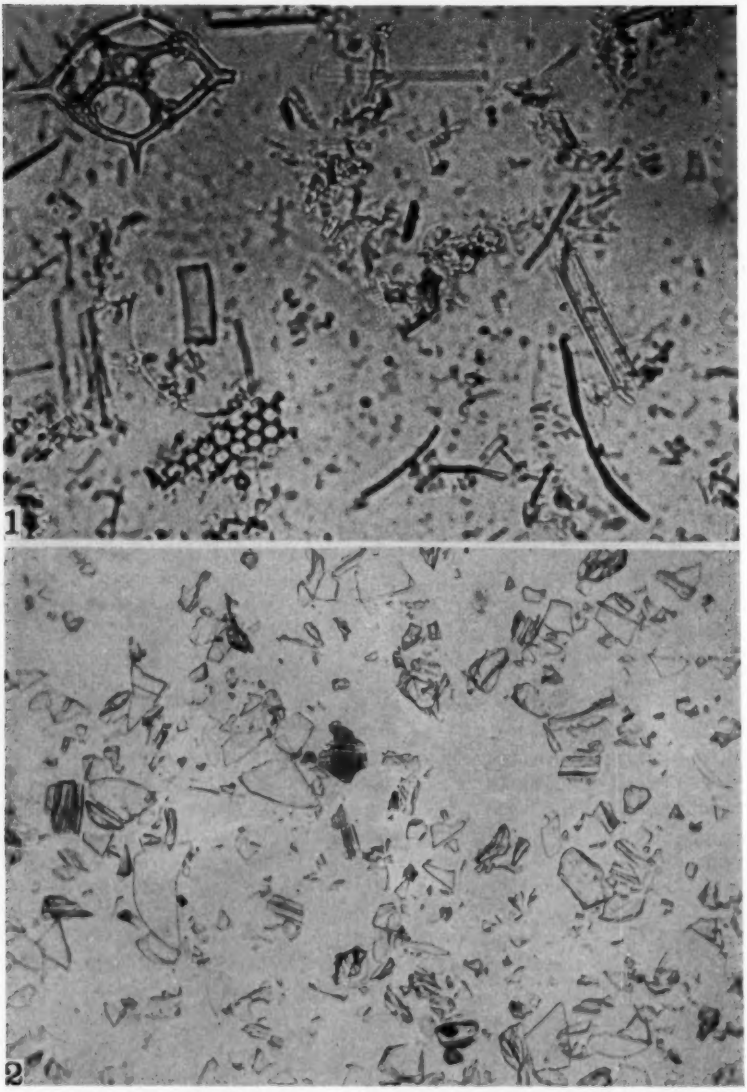


FIG. 1. Photomicrograph of diatomite, Monterey formation, Lompoc, California. Note irregular shape and porosity of the particles. × 720.

FIG. 2. Photomicrograph of rhyolite pumicite, White River formation (?) near Sterling, Colorado. Note angularity of the particles. × 80.

Some pozzolanic materials are excessively fine, and the particles may be highly porous, angular, or irregular in shape (Figs. 1 and 2). These characteristics lead to high water requirement for given workability of the mix, with consequent excessive drying shrinkage, low strength, and possibly reduced resistance to freezing and thawing of the concrete. Fly ash is composed largely of spherical particles (Fig. 3), and water requirement for given workability consequently is reduced.

Chemically, pozzolans decrease susceptibility of the hydrated portland cement to dissolution or deterioration by reaction with the calcium hydroxide released by hydration of the portland cement. Reactive substances of the pozzolan are converted by reaction with calcium hydroxide into comparatively stable compounds, many of which are cementitious. Also, because the pozzolanic reactions proceed slowly, portland-pozzolan cement concretes harden slowly and usually, but not always, increase progressively in strength and durability for long periods of time. Those pozzolans which inhibit or prevent cement-aggregate reaction in concrete do so by chemical reaction with or absorption of the alkalies (Na_2O and K_2O) released by the hydrating portland cement. The alkalies thus bound by the pozzolan are unable to attack the aggregate.

The physical and chemical properties of pozzolans depend upon the mineralogic or compound composition and the physical characteristics of the source material and the processes to which the materials have been subjected during manufacture of the finished product. Chemical analysis alone will not indicate the pozzolanic activity of materials unless the process of beneficiation causes complete reconstitution of the components. Inasmuch as production of pozzolans rarely involves calcination to fusion temperatures, pozzolans may be classified according to the original minerals or compounds which themselves account for the chemical activity of the pozzolan or whose reconstitution during processing gives rise to active substances.

Activity Type.—Natural pozzolans include originally pozzolanic materials and natural materials in which pozzolanic activity can be induced by heat treatment. Natural pozzolans owe their chemical activity to one or more of five substances; namely (1) volcanic glass, (2) opal, (3) clay minerals, (4) zeolites, and (5) hydrated oxides of aluminum. Artificial pozzolans, including fly ash,[6] ground brick, burned oil shale, and others, owe their chemical activity to glasses produced by fusion or reconstitution of the ingredients of the original material. Artificial pozzolans will not be discussed further in this paper because the geologist will be concerned but little with location, testing, or use of these materials.

Based upon the identity of the essential active ingredient, natural pozzolans and pozzolans produced by calcination of natural materials at temperatures less than 2,000° F can be classified as follows:

[6] Fly ash is a flue dust precipitated from the stacks of boilers in which pulverized coal is used as fuel. This material is being used as pozzolan in construction of Hungry Horse and Canyon Ferry Dams, Montana.

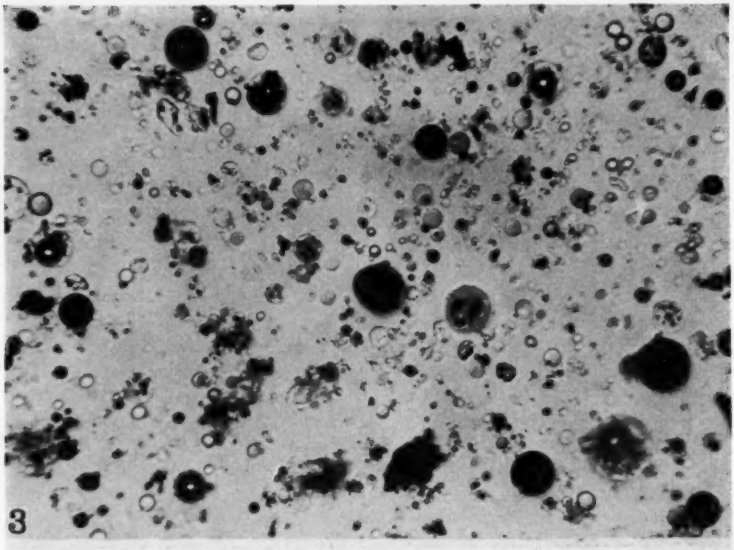


FIG. 3. Photomicrograph of typical fly ash, State Line Plant, Chicago, Illinois. Note spherical shape of the particles. × 490.

FIG. 4. Deposit of rhyolite pumicite, Friant formation, near Friant, California, used in construction of Friant Dam.

Activity type	Active ingredient
1	Volcanic glass
2	Opal
3a	Kaolinite-type clays
3b	Montmorillonite-type clays
3c	Illite-type (hydromica) clays
3d	Mixed clays with altered vermiculite [7]
3e	Palygorskite
4	Zeolites
5	Hydrous aluminum oxides
6	Nonpozzolans

Although the properties of pozzolanic materials largely depend upon their geologic origin and mineralogic composition, the petrographic classification of a pozzolan may not indicate the identity of the active substances. For example, volcanic ashes and tuffs usually owe their pozzolanic activity to rhyolite glass, but many ashes and tuffs contain opal, clays, or zeolites whose inherent chemical properties differ from those of the glass, and some altered volcanic materials owe all of their pozzolanic activity to substances other than glass. The possible ambiguity of the petrographic classification is avoided through designation of activity type. Also, from these remarks, it will be evident that many pozzolans may be designated as "mixed activity types" because they contain active ingredients of several types, such as opal and clay, glass and opal, or kaolinite and beidellite. On the other hand, designation of activity type will not indicate reliably the quality of a material as a pozzolan, inasmuch as the proportion of active ingredients may vary within wide limits. Moreover, fineness and particle size distribution strongly influence pozzolanic activity of all pozzolans.

The activity types include the following important pozzolans designated according to petrographic classification:

Activity type	
1	Rhyolite pumicites and tuffs
	Dacite pumicites and tuffs
1, 3a [8]	Altered pumicites and tuffs
1, 3b	
2	Diatomite and diatomaceous earth
	Opaline chert
2, 3b	Opaline shales
3a	Kaolin clays
3b	Bentonitic clays and shales
	Fuller's earth
3c	Hydromica (illite), clays and shales
3d	Glacial clays and silts
3e	Attapulgus clay
4	Zeolitic tuffs and ashes
5	Bauxite

Natural pozzolans used in important construction in the United States are indicated in Table 1.

[7] A characteristic mixture of altered vermiculite, beidellite-nontronite, illite, and kaolinite, constituting 30 to 50 percent of lacustrine silts and clays of the Nespelem formation in the State of Washington.

[8] Mixed activity type owing activity to both volcanic glass and kaolinite-type clay.

TABLE 1.

GEOLOGIC OCCURRENCE AND ACTIVITY TYPE OF NATURAL POZZOLANS USED IN CONSTRUCTION IN THE UNITED STATES.

Source formation	Locality	Petrographic classification	Active ingredients	Activity type	Engineering structures
Monterey	Near Santa Cruz, California	Opaline shale and chert	Opal and beidellite	2, 3b	Golden Gate and San Francisco Bay Bridges and highway pavements, California
	Near Casmalia, California	Oil-impregnated shale	Beidellite	3b	Big Creek Dam No. 7, Fresno County, California
Puente	Near Colton, California	Opaline shale and chert	Opal and beidellite	3b, 2	San Jacinto Tunnel, near San Jacinto, California; Davis Dam, Nevada-Arizona
Friant	Near Friant, California	Pumicite	Rhyolite glass	1	Friant Dam; Pardee Dam; Canal structures, California
Rosamond	Near Monolith, Hiawee, and Fairmont, California	Altered tuff	Clinoptilolite and beidellite	4	Los Angeles Aqueduct, California
Bottom sediments, San Francisco Bay, California	Near Redwood City, California	Argillaceous silt	Illite- and montmorillonite-type clay	3c, 3b	Bonneville Dam, Washington-Oregon
Mowry	Near Laramie, Wyoming	Siliceous shale	Beidellite	3b	Experimental highway pavements, Kansas
Ogallala (?)	Near Hobart, Oklahoma	Pumicite	Rhyolite glass	1	Altus Dam, Oklahoma
Sonora volcanics	Near Napa, California	Diatomite	Opal	2	East Bay Sewage Project, Oakland, California

Activity Type 1.—Pozzolans of Activity Type 1 include rhyolite tuffs and pumicites and some dacite tuffs and pumicites (Fig. 2). Experience may show the value of some andesitic tuffs and ashes. Andesites, basalts, and basaltic tuffs and ashes are inferior or wholly unsatisfactory in quality. Trachytic and phonolitic tuffs and ashes used since ancient times in Germany, France, and Italy apparently require hydrothermal alteration with production of clays and zeolites before satisfactory activity is induced.[9] Glassy lavas and shallow intrusive igneous rocks containing a high proportion of acidic glass occasionally might be suitable as pozzolan, but grinding costs would be excessive.

Pozzolans of Activity Type 1 owe their activity primarily to volcanic glass, whose refractive index lies in the range 1.490 to 1.507; but all ashes and tuffs contain essentially nonreactive minerals, as well as opal, clays, or zeolites which are also pozzolanic. Experience indicates that pozzolans owing their activity exclusively to volcanic glass ordinarily must contain glass to the extent of 60 percent or more in order to develop satisfactory mortar strength. Similarly, volcanic glass must constitute 90 percent or more of pozzolans achieving control of alkali-aggregate reaction in mortar unless other active ingredients are present. Conversely, however, not all volcanic ashes and tuffs containing these proportions of glass will necessarily cause development of satisfactory strength or will control satisfactorily the progress of alkali-aggregate reaction in mortar or concrete. Inferior quality of pozzolans containing high proportions of active constituents may demonstrate exceptional stability of these constituents or excessive coarseness of the material. On the other hand, some volcanic pozzolans increase the rate of alkali-aggregate reaction through release of alkalies from their own substance during interaction with portland cement.

Activity of individual rhyolite glasses cannot be predicted from refractive index or other microscopical observations, nor has their activity been correlated with details of chemical composition (Table 2). However, the spacing and intensity of certain lines in an X-ray diffraction pattern can be related to potential alkali reactivity of glasses.

Volcanic pozzolans usually require grinding to achieve fineness sufficient to develop the desired physical properties and chemical activity in mortar and concrete. However, rhyolite pumicites from deposits in several states are naturally sufficiently fine to be used directly or after drying and milling. For example, in a study of Pliocene and Pleistocene rhyolite ashes from western Kansas and adjacent parts of Nebraska, Texas, and Oklahoma, Swineford and Frye[10] found that the proportion passing the No. 230 sieve varied from 4.6 to 99.9 percent by weight. On the other hand, samples of rhyolite pumicite have been obtained from deposits in Lassen, Calaveras, Madera, and Fresno Counties, California; and Travis County, Texas, in which materials passing the No. 325 sieve constitute more than 90 percent of the whole.

[9] Lea, F. M., op. cit.

[10] Swineford, Ada, and Frye, J. C., Petrographic comparison of Pliocene and Pleistocene volcanic ash from western Kansas: Univ. Kansas Pub., Kansas State Geol. Survey Bull. No. 64, Pt. 1, pp. 1–32, 1946.

TABLE 2.

PROPERTIES AND COMPOSITION OF THE GLASS AND POZZOLANIC QUALITY OF TWO RHYOLITE PUMICITES.

Pumicite		Characteristics of the glass [1]								Glass content of pumicite	Mortar expansion (percent of control) [2]	Mortar strength (percent of control) [3]
		Chemical composition (percent)						Index of refraction	Absolute specific gravity			
No.	Source	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Ignition loss					
40	Ogallala formation near Ellis, Kansas	71.44	13.08	1.80	0.27	2.22	3.32	1.495	2.355	98	2	113
4	Friant formation near Friant, California	73.98	13.70	1.22	0.45	1.97	3.59	1.495	2.341	90	10	95

[1] Glass analyzed after separation from crystals. E. Lyons, Analyst.

[2] At 2 weeks' age test mortar has expanded indicated percentage of expansion of control specimen containing no pozzolan, but same cement and aggregate.

[3] At 28 days' age test mortar exhibits compressive strength equivalent to indicated percentage of compressive strength of control specimen containing no pozzolan but same cement and aggregate.

At an age of 90 days, the compressive strength of the mortars containing pozzolans of Activity Type 1 has been found to range from 64 to 131 percent of the strength of the control portland cement mortar containing no pozzolan, a relative compressive strength of 80 percent at this age usually demonstrating adequate activity. Compressive strength of these portland cement-pozzolan mortars increases with temperature of calcination of the pozzolan, usually obtaining a maximum after calcination of the pozzolan at 1,000° to 1,600° F. For pozzolans of Activity Type 1, specific gravity, grindability, water requirement, and setting time of lime-pozzolan pastes show little change with calcination of the pozzolan up to 1,800° F. The effect of pozzolans of Activity Type 1 upon resistance to attack by sulfate-containing waters varies greatly with composition and fineness of the pozzolan.

The tested pozzolans of Activity Type 1 reduce mortar expansion resulting from the alkali-aggregate reaction at 90 days' age to 14 to 78 percent of that of the control specimen containing no pozzolan. In this test a reduction to 25 percent of the expansion of the control specimen is considered to be satisfactory. Alkali reactivity of rhyolite pumicites typically is reduced somewhat by calcination, particularly after heating at 1,800° F.

With introduction of other active ingredients, the properties of pozzolans of Activity Type 1 grade progressively to those of pozzolans of Activity Types 2, 3a, 3b, 3c, and 4.

Activity Type 2.—Pozzolans of Activity Type 2 include diatomite (diatomaceous earth) and cherts owing their activity to opal. Although diatomaceous sediments and opaline cherts owe their activity to the same ingredient, they differ widely in physical properties because of differing particle size, particle shape, and intraparticulate porosity. Pozzolans of Activity Type 2 are the most active of all natural pozzolans.

Diatomaceous earth and diatomite are composed of broken tests of diatoms, which typically are disklike, rodlike, spindleshaped, or highly irregular in shape, and which possess an intricate system of internal pores (Fig. 1). These characteristics lead to high water requirement for given workability of mortar and concrete, with consequent reduction in strength and weathering resistance and increase in drying shrinkage. Water requirement can be reduced by fine grinding, calcination, and use of additives. However, diatomite and diatomaceous earth must be used with caution as pozzolans in concrete construction subjected to prolonged drying or wetting and drying conditions.[11]

Diatomaceous earth and diatomite are exceedingly fine, usually ranging between 17,000 and 45,000 cm^2/g in specific surface area (Lea-Nurse method),[12] and with slight grinding to break up aggregated lumps, the raw materials will meet fineness requirements.

Compressive strength of portland cement-diatomite mortar at an age of 90 days varies from 64 to 112 percent of the compressive strength of the control

[11] Diatomaceous earth has been used successfully as an additive generally to the extent of 1½ to 3 percent by weight of the portland cement to improve workability and reduce segregation and bleeding of water.

[12] Lea, F. M., and Nurse, R. W., The specific surface of fine powders: Soc. Chem. Industry Jour., vol. 58, pp. 277–283, 1939.

mortar containing no pozzolan. Mortar strength typically increases with calcination of the diatomite, reaching a maximum when the pozzolan has been calcined in the range 1,400° to 1,800° F. Specific gravity typically increases, and time of set, grindability, and water requirement decrease with calcination up to 2,000° F. Resistance of mortar to attack by sulfate-bearing solutions is increased by introduction of diatomaceous earth, possibly as much as sixfold over that of straight portland cement mortar.

Diatomite and diatomaceous earth are highly reactive with cement alkalies, but the high water requirement has precluded use of sufficient pozzolan to effect permanent control of the alkali-aggregate reaction in exposed mortar and concrete.

Opaline cherts possess the inherent chemical reactivity of diatomite, but are free from the objectionable internal porosity which leads to high water requirement. At 90 days age portland-pozzolan cement mortar containing pulverized, raw, opaline chert from the Monterey formation, California, possessed 92 percent of the compressive strength of the control specimen; and after calcination of the pozzolan at 1,400° F, mortar expansion as the result of alkali-aggregate reaction was only 4 percent of that of the control specimen. Opaline cherts are the most effective pozzolans available for control of alkali-aggregate reaction.

Opaline shales and porcelanites of the Monterey, Salinas, Puente, and equivalent Miocene formations of southern California, represent Activity Types 2 and 2, 3b, inasmuch as they owe their activity to either opal or both opal and beidellite. Calcination at 1,400° F reduces water requirement and induces maximum alkali reactivity. Pulverized and calcined cherty shale and porcelaneous rock from these formations are capable of controlling alkali-aggregate reaction in mortar and concrete. .These materials greatly improve resistance of cement to attack by sulfate-bearing water.

Activity Type 3.—All clayey pozzolans must be calcined at temperatures over 1,000°F to induce optimum activity and reduce water requirement. Activity of kaolinite (Activity Type 3a), illite (hydromica) (Activity Type 3c), mixed clays with altered vermiculite (Activity Type 3d) and palygorskite (Activity Type 3e) is developed by amorphous substances produced by disintegration of the structure of the original crystalline compounds. Activity of montmorillonite-type clays (Activity Type 3b) relates to changes in the crystalline structure but not complete disintegration. Optimum activity of kaolinite is developed after calcination at temperatures between 1,000° and 1,800° F. Montmorillonite-type clays are activated by calcination in the range 1,000° to 1,800° F, but data suggest that glasses produced by sintering at about 2,200° F are also active to a satisfactory degree. Illite (hydromica) and mixed clays with altered vermiculite achieve satisfactory activity only following calcination at temperatures at or above 1,800°F. All clayey pozzolans require grinding to develop proper fineness.

Calcination also is necessary for pozzolans of Activity Types 3a, 3b, and 3e to control the alkali-aggregate reaction. Pozzolans of Activity Type 3c always are inferior in this regard, and pozzolans of Activity Type 3d probably will also be found to be inferior, although no tests have been performed to demonstrate

the alkali reactivity of Activity Type 3d. Pozzolans owing their activity to kaolinite must contain 75 per cent or more of that mineral to control alkali-aggregate reaction. Montmorillonite-type clays containing sodium as the exchangeable cation increase the deleterious effects of the alkali-aggregate reaction through release of the sodium into the mortar. Kaolin calcined at 1,650° F greatly increases sulfate resistance of mortar.

Activity Type 4.—Pozzolans of Activity Type 4 owe their activity to zeolites. Among materials tested in the Bureau of Reclamation laboratories, representatives of this group owe their activity to clinoptilolite (silica-rich heulandite), ptilolite and analcite. Undoubtedly, other zeolites will contribute different physical properties to the pozzolans.

In laboratory tests of deeply altered rhyolite tuffs from the Rosamond series of California containing clinoptilolite to the extent of about 80 percent of the material, the portland-pozzolan cement mortars show satisfactory compressive strength, tensile strength, and resistance to attack by sodium sulfate solution. Water requirement is moderately high, but freezing and thawing durability of the concrete is not affected adversely. Activity of the altered tuff is improved by calcination to 1,400° F. Tests of pulverized analcite-containing phonolite porphyry from Missouri Buttes, Wyoming, demonstrate that sodium and potassium are released and will cause the alkali-aggregate reaction if susceptible aggregates are used.

The altered tuff of Activity Type 4 is inadequate for control of alkali-aggregate reaction, and in some mixes expansion due to this reaction is increased. Leach tests demonstrate that altered tuff from the Rosamond series near Monolith, California, will release into distilled water, soda and potassa equivalent to 0.43 percent by weight of the tuff. These alkalies will augment the supply of cement alkalies available to carry out the alkali-aggregate reaction.

Activity Type 5.—No data on pozzolanic properties of pozzolans of Activity Type 5 are available.

Activity Type 6.—Materials of Activity Type 6 include stable minerals which are essentially nonreactive with lime. Included in this group are such common minerals as quartz, the feldspars, carbonates, amphiboles, pyroxenes, micas, and most of the rock-forming minerals. When finely ground, these substances act as inert fillers in mortar and concrete. Calcination to clinkering temperatures may induce pozzolanic properties; with a suitable admixture of carbonates and clays, heating to sintering or clinkering temperatures and fine grinding will produce hydraulic cements.

GEOLOGICAL OCCURRENCE OF NATURAL POZZOLANS.

Natural pozzolans occur throughout the United States, but tested sources of satisfactory materials mainly are west of the Mississippi River. Many geologic formations are known to yield suitable materials which can be used either in their original condition or more commonly after calcination at temperatures less than 2,000° F and grinding.[13]

[13] For economy of space a table summarizing test data and mineralogic analyses of 95 materials catalogued according to source geologic formation has been omitted from the paper. This table will be made available to interested readers on request.

Pozzolans of Activity Types 1 and 2 are confined largely to the western states, where they occur in deposits of Tertiary and Quaternary ages (Figs. 4, 5, 6, and 7). It is probable that their absence from older formations relates to progressive alteration and recrystallization of the unstable volcanic glass and opal to more stable substances with passage of time and influence of geologic processes. Pozzolans of Activity Type 1, particularly rhyolite pumicites and

FIG. 5. Close-up view of stratified rhyolite pumicite, Friant formation, near Friant, California.

tuffs, are the most common sources of natural pozzolans. They are to be found in all of the western states, frequently with little contamination.

Deposits yielding tested pozzolans of Activity Types 3a, 3b, 3d, and 3e range in age from Cretaceous to Quaternary; and pozzolans of Activity Type 3c range in age from Cambrian to Recent. Satisfactory tested pozzolans of Activity Type 4 are altered tuffs of Miocene age; additional investigations may reveal zeolitic pozzolans of other geologic age. Materials of Activity Type 5

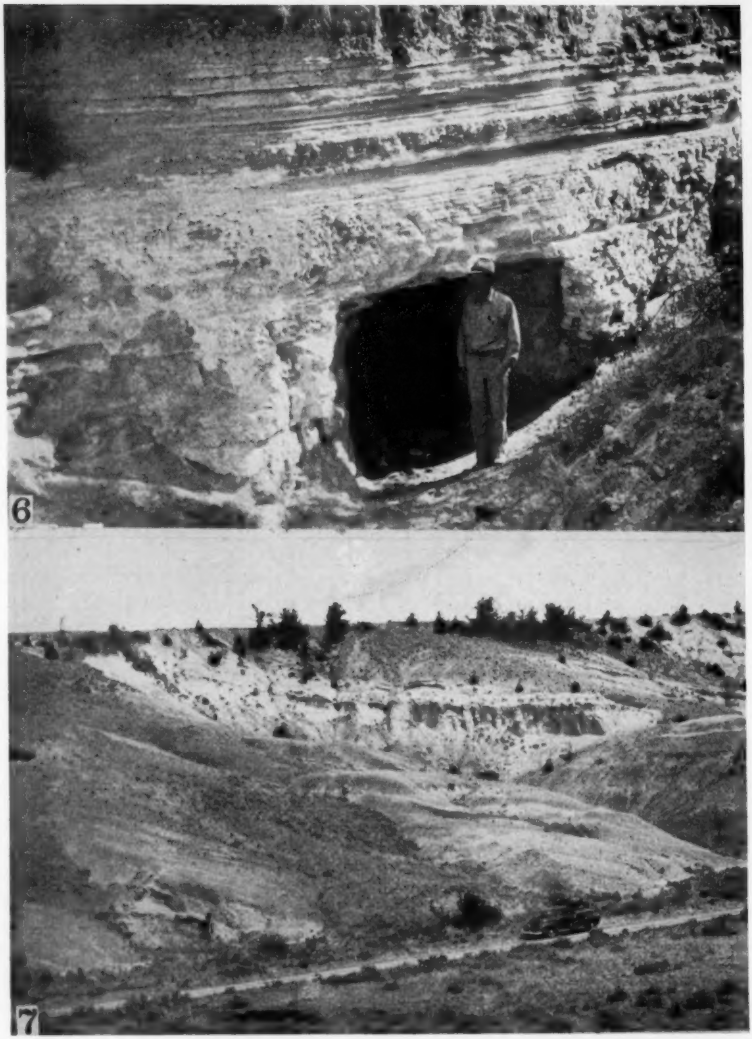


FIG. 6. Rhyolite pumicite, Valley Springs formation, near Wallace, California.

FIG. 7. Lenticular deposit of rhyolite pumicite contaminated with sand and gravel, Bozeman formation, near Winston, Montana.

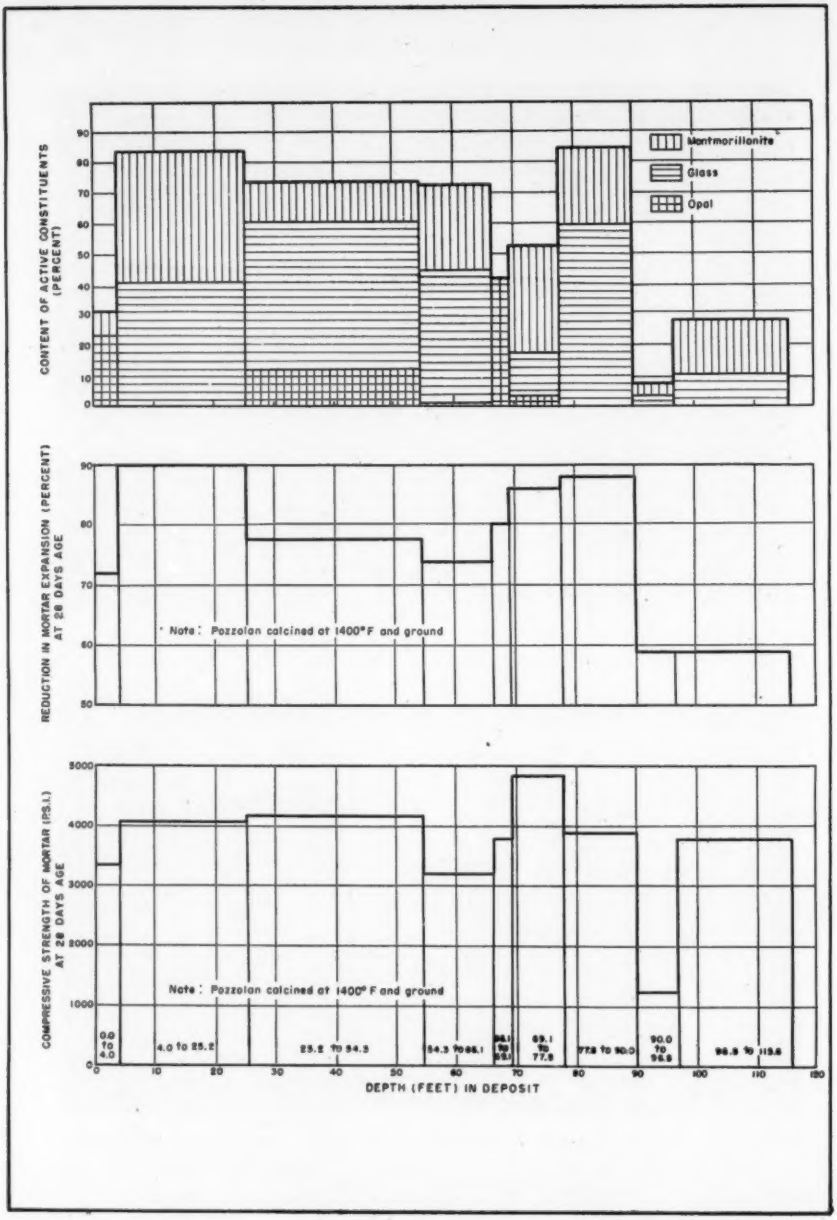

CONTENT OF ACTIVE CONSTITUENTS (PERCENT)
Montmorillonite
Glass
Opal
REDUCTION IN MORTAR EXPANSION (PERCENT) AT 28 DAYS AGE
* Note: Pozzolan calcined at 1400° F and ground
COMPRESSIVE STRENGTH OF MORTAR (PSI.) AT 28 DAYS AGE
Note: Pozzolan calcined at 1400° F and ground
0.0 to 4.0
4.0 to 25.2
25.2 to 54.3
54.3 to 65.1
65.1 to 69.1
69.1 to 77.5
77.5 to 90.0
90.0 to 96.5
96.5 to 115.6
DEPTH (FEET) IN DEPOSIT

FIG. 8. Relationships of depth in the deposit to properties of pozzolan, Bozeman formation, near Winston, Montana.

have not been tested as pozzolans in the laboratories of the Bureau of Reclamation, and reports of such tests of bauxite from deposits in the United States have not been found in the literature.

All satisfactory natural pozzolans occur in stratified deposits; consequently, they are usually highly variable in composition, texture, and properties. For example, the lacustrine deposits of the Bozeman formation of western Montana contain few relatively uncontaminated beds of pumicite and even these grade rapidly horizontally and vertically into bentonite, friable sandstone, and poorly consolidated conglomerate (Fig. 7). Consequently, potential pozzolanic activity varies widely in the deposit (Fig. 8). Similarly the opaline shales and cherts of the Monterey, Salinas, Puente, and other Miocene formations of southern California always are associated with clay shales, sandstones, siltstones, and other facies of little value as pozzolan, which must be avoided or wasted during exploitation. In tests of 31 samples of calcined and ground pozzolan from one quarry in the Puente formation, compressive strength of lime-pozzolan mortar ranged from 1,660 psi to 1,070 psi, and mortar expansion as the result of alkali aggregate reaction ranged from 4 percent to 33 percent of that of the control specimens containing no pozzolan.[14]

CONCLUSIONS.

Interest in use of pozzolans in concrete construction is increasing and will gain impetus as their properties are understood more fully, as suitable sources are discovered, and as means of beneficiation are developed. Natural pozzolans and materials in which pozzolanic qualities can be induced by calcination are to be found in geologic formations ranging in age from Cambrian to Recent, in most parts of the United States.

Materials owing their activity to rhyolite glass and opal are the best sources of natural pozzolans. Clayey pozzolans are more widespread, but strength development typically is inferior. The activity of zeolites and aluminous pozzolans will depend upon the characteristics of the active compound.

Except for unusual occurrences of exceedingly fine-grained pumicites in California and Texas, all natural pozzolans require grinding to develop fineness sufficient for use as a cement admixture. In addition, many natural pozzolans require calcination at temperatures over 1,000° F to develop optimum activity and reduce undesirable qualities, such as excessive water requirement. For pozzolans owing their activity to volcanic glass and opal, calcination at temperatures up to 1,800° F causes no consistent change in properties; at higher temperatures activity declines. Pozzolans owing their activity to kaolinite, montmorillonite-type clays, and palygorskite develop optimum activity after calcination in the range 1,000° to 1,800° F, although data suggest that some montmorillonite-type clays are converted to active glasses with calcination at temperatures about 2,200° F. Pozzolans owing their activity to illite (hydromica) and mixed clays with altered vermiculite show low degrees of activity unless calcination is carried to at least 1,800° F.

[14] Tests performed in accordance with Bureau of Reclamation Specifications No. 1904.

ACKNOWLEDGMENTS.

The authors express their gratitude to members of the Research and Geology Division, Branch of Design and Construction, Bureau of Reclamation, for assistance in conduct of the investigations and preparation of this paper. The photomicrographs were prepared by W. Y. Holland. Several of the petrographic analyses of pozzolans were made by M. E. King. Tests of mortars were performed under the direction of L. P. Witte and O. J. Glantz.

U. S. BUREAU OF RECLAMATION,
DENVER, COLORADO,
November 14, 1950.

STABILIZATION OF SOME ROCKSLIDES IN GRAINGER COUNTY, TENNESSEE.[1]

ROBERT A. LAURENCE.

ABSTRACT.

Slides in dipping Cambrian sandstone, resulting from highway relocation along Norris Reservoir, have been stabilized by the use of steel dowels and concrete anchor blocks. Geologic conditions favored this type of treatment, as sliding took place in thin shales between thick sandstone beds.

INTRODUCTION.

DIP-SLOPE slides in highway and railroad cuts and other excavations are fairly common throughout the area of folded Paleozoic rocks in the Appalachians. Conditions are favorable to dip-slope sliding wherever the rocks dip steeply and the slope of the cut is steeper than the dip of the rocks and is inclined in the same direction. The slides are less common in thick-bedded limestone and dolomite formations like those of the Knox group than in shale formations like the Athens and Sevier shales or in formations of interbedded sandstones and shales like the Rome and the Clinton formations. They are especially prevalent in these last two formations, because the thick sandstones make prominent ridges whose slope is parallel to the dip of the beds so that usually it is impossible, or at least impractical, to make the side of the cut less steep than the dip of the rocks.

The purpose of this report is to describe an example in which remedial measures applied when sliding first began, shortly after construction of the road, were effective in stabilizing the cut and have prevented further sliding during the 14 years since the work was done. This work was done by the Tennessee Valley Authority, on the Indian Creek Road (project no. 5020–7634) in Grainger County, Tennessee, 500 feet east of its intersection with U. S. Highway 25E (Tennessee 32), approximately 28 miles south of Middlesboro, Ky., and 23 miles north of Morristown, Tenn. (Fig. 1.)

ACKNOWLEDGMENTS.

Acknowledgment is made to the Highway Section, Engineering Design Department, Tennessee Valley Authority, for use of their construction drawing upon which Figure 3 is based and from which construction data and quantities were obtained. The base map for Figure 2 consists of parts of two TVA-USGS quadrangle maps—Avondale (162 SW) and Howard Quarter (162 NW).

[1] Published by permission of the Director, U. S. Geological Survey.

GEOLOGIC SETTING.

Areal geology in the vicinity of Indian Creek is shown on the geologic map, Figure 2. The following formations are present in the area:

Age	Formation	Approximate thickness (feet)
Middle Ordovician	Chickamauga limestone	1200
Lower Ordovician and Upper Cambrian	Knox group	2550
Upper Cambrian	Nolichucky shale	
	Maynardville limestone member	170
	Shale member	600
Middle Cambrian	Maryville limestone	550
	Rogersville shale	225
	Rutledge limestone	140
	Pumpkin Valley shale	350
Lower Cambrian	Rome formation	*475

* Only the upper 475 feet is present, above the Copper Creek fault.

The Rome formation in this area consists chiefly of thin-bedded siltstones and shales, with three dolomite zones 20 to 40 feet thick in the lower part, and several interbedded sandstones, in beds from a few inches to 6 feet thick, especially in the upper part. The beds strike rather uniformly northeast (N 60°–70° E) and dip 30° S. The area of the Rome outcrop is bounded on the northwest by the trace of the Copper Creek overthrust, a southeast-dipping thrust

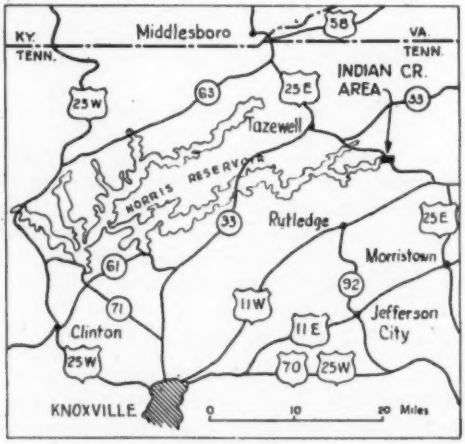


FIGURE 1
INDEX MAP SHOWING INDIAN CREEK AREA, TENNESSEE

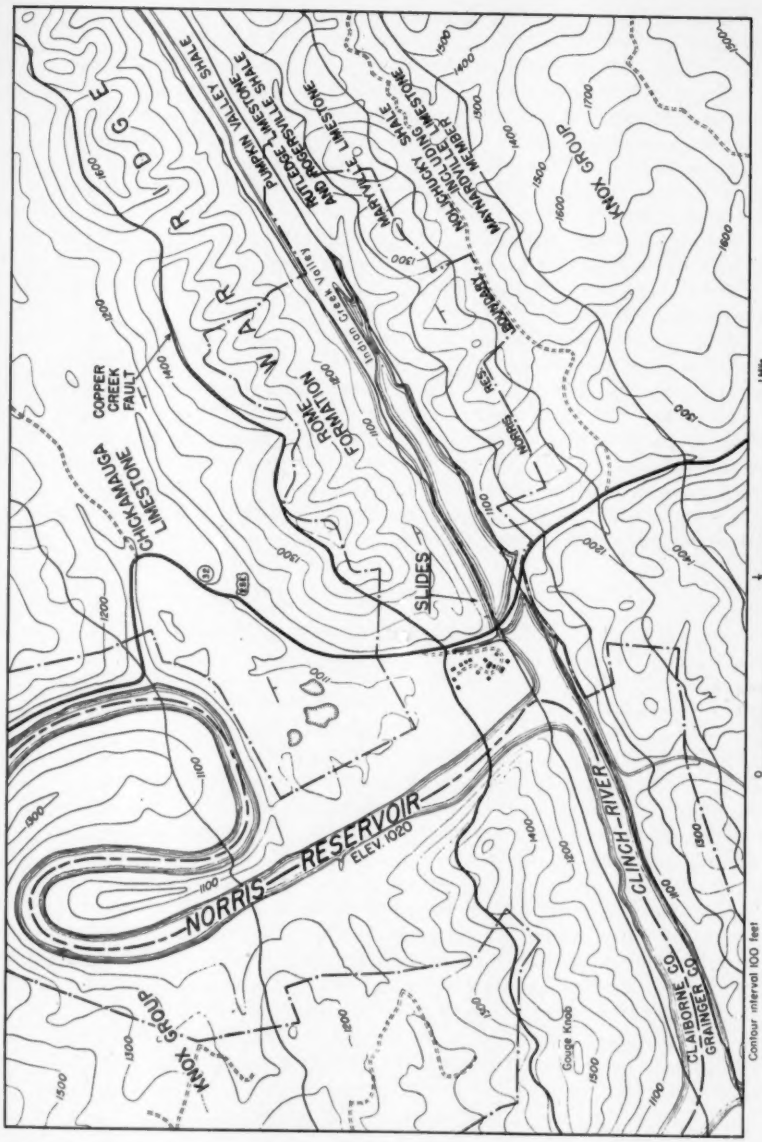


FIGURE 2
GEOLOGIC MAP OF THE INDIAN CREEK AREA
GRAINGER COUNTY, TENN.

fault. The lithology of the Rome formation in this region has been described by Rodgers and Kent.[2]

War Ridge, with its southwest extension, Gouge Knob, is a long, continuous, strike ridge held up by the hard sandstones in the upper part of the Rome formation. Its uneven crest is 400 to 600 feet higher than the adjacent valleys. It is broken at several places by water gaps, which provide access through the ridge for both major and secondary roads. Immediately southeast of War Ridge is the long, straight valley of Indian Creek, which has been developed on the weak Pumpkin Valley shale.

Construction of Norris Dam, and filling of its reservoir to the 1,020-foot contour, in 1936, flooded the lower end of Indian Creek Valley to a depth of 15 to 20 feet. It was thus necessary to raise both U. S. Highway 25E and the southwestern 2,500 feet of the Indian Creek Road. The latter required cutting into the dipping beds of the upper part of the Rome formation at the foot of the southeast slope of War Ridge, and conditions favorable to dip-slope sliding were thus produced. It would have been impractical to cut this slope parallel to the dip of the rocks, as this would have extended the cut 400 feet to the top of the ridge and would have required additional excavation of more than 15,000 cubic yards of rock for each 100 feet of length along the highway. Although the road could have been located on the opposite side of the valley, this would have required a large amount of rock excavation in the steep bluff of Rutledge limestone, as well as a bridge over Indian Creek.

LANDSLIDES AND CORRECTIVE MEASURES.

Sliding began shortly after the cuts between stations 4 + 50 and 6 + 50 were completed (Fig. 3). Fortunately, the slides were neither sudden nor catastrophic, and only the lower 40 feet of the slope was affected. The surface on which the sliding took place is the top of a 22-inch fine-grained slightly banded sandstone bed, which is separated from an overlying 28-inch sandstone bed by a 2-inch bed of shale and siltstone and 4 inches of thin-bedded sandstone (Fig. 4). Had the 2-inch layer of shale and siltstone not been present, it is quite probable that no sliding would have occurred. However, once sliding was under way, it probably would have continued until all material overlying the 22-inch sandstone bed, to the top of the ridge, would eventually have come down on the road.

To prevent this further sliding, the work shown in Figure 3 was done by the Tennessee Valley Authority. As shown in Figure 4, 2½-foot steel dowels, 2 inches in diameter, were grouted in holes drilled 18 inches into the 22-inch sandstone bed, near the upper edge of the slide area. These were spaced about 6½ feet apart, and at each position two dowels were placed, one at right angles to the bedding surface, the other at a 45° angle to the bedding, or 60° and 15°, off horizontal. The dowels were anchored with blocks of concrete 18 inches high, 19 inches wide, and 26 inches long, reinforced with ½-inch steel tie bars

[2] Rodgers, John, and Kent, D. F., Stratigraphic section at Lee Valley, Hawkins County, Tennessee: Tennessee Div. Geology Bull. 55, pp. 4–7, 1948.

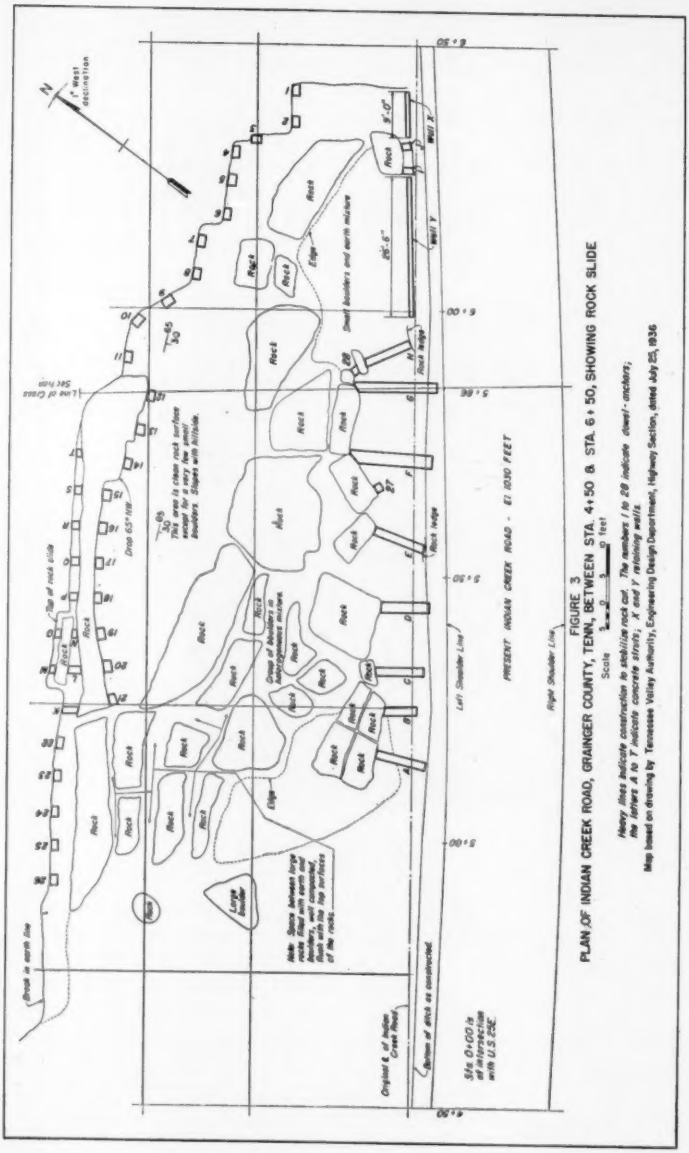

N
7° West declination
Rock
Right
Edge
Small boulders and earth mixture
Rock ledge
Wall 1'
Wall 2'
Left Shoulder Line
Right Shoulder Line
PRESENT INDIAN CREEK ROAD - EL 1035 FEET
Large rock
Drop 63'-118'
Top of rock cliff
Line of Cross Section
Drain in earth line
Original C. of Indian Creek Road
Junction of ditch as constructed
Sta. 0+00 is 69 ft. from Sta. 10+00 on U.S. 25E
Note: Slope between large rocks is filled with earth and boulders, and is flush with the top surfaces of the rocks.
Group of boulders in conglomerate mixture.
Heavy lines indicate construction to stabilize rock cut. The numbers 1 to 28 indicate dowel-anchors; the letters A to F indicate concrete struts; A cut 1' retaining walls.
Map based on drawing by Tennessee Valley Authority, Engineering Design Department, Highway Section, dated July 25, 1936

FIGURE 3.

PLAN OF INDIAN CREEK ROAD, GRAINGER COUNTY, TENN., BETWEEN STA. 4+50 & STA. 6+50, SHOWING ROCK SLIDE

Scale 1 0 1 2 3 0 feet

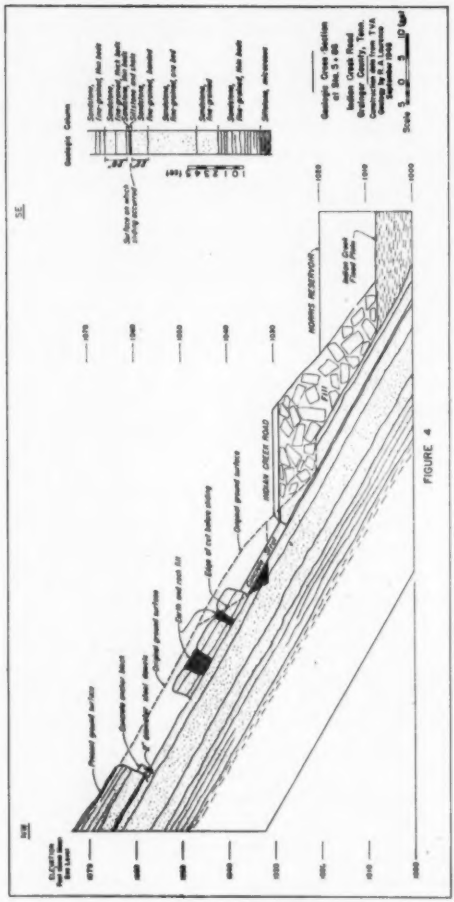


FIGURE 4

(Fig. 5). The uphill side was placed directly against the edge of the 28-inch sandstone bed or (nos. 12 to 21) the lower edge of a large sandstone block which had already moved about 3 feet down the dip. Two others (nos. 27 and 28) were placed against small rocks near the bottom of the slide. Twenty-eight of these anchors were built, using 5.24 cubic yards of concrete, 180 pounds of reinforcing steel, and 1,403 pounds of dowel steel.

In addition to the dowel anchors, 20 concrete struts, 8 of which were reinforced with ½-inch and ¾-inch steel tie bars, were built. These are approximately 18 inches high and vary in length and width as shown in Figure 3. Ten of these support large sandstone blocks which had already moved several feet

FIG. 5. A dowel anchor block. (Rule is 4 feet long and vertical. Hammer rests on 22-inch sandstone bed.)

down the slope. The struts rest against the 28-inch sandstone bed beneath the road. The spaces between the large boulders were filled with earth and boulders, well compacted. However, the large space below the dowel anchors was not filled, and the upper surface of the 22-inch sandstone bed is exposed throughout this area. The other struts provide support to the sandstone ledge above the middle portion of the slide area and rest against the large block which is supported by dowel anchors 12 to 21. The concrete struts required 12.56 cubic yards of concrete and 829 pounds of reinforcing steel.

Two retaining walls, 26½ feet and 9 feet long, were built at the northeast edge of the slide area, to support a mass of small rocks and earth. These were

placed at least 3 inches into bedrock and are 10 inches wide at the top. They contain 9.96 cubic yards of concrete and 104 pounds of reinforcing steel.

As a result of the sliding and construction work, it was necessary to shift the center line of the new road approximately 14 feet to the south in the slide area and to lower the road about 3 feet to an approximate elevation of 1,030 feet.

The work described above was done during the summer of 1936. The road has been in continuous service since then, and the slide area has given no further trouble. The writer has observed the job at intervals through this 14-year period, and the most recent examination, in June 1950, showed the cut to be as effectively stabilized now as it was when the work was completed.

U. S. GEOLOGICAL SURVEY,
KNOXVILLE, TENN.,
Oct. 17, 1950.

SCIENTIFIC COMMUNICATIONS

NOTES ON THE USE OF POLARIZATION FIGURES, AND CORRECTIONS.

During the past year, the writer introduced the subject of polarization figures and rotation properties [1] to a class of 14 students in mineragraphy. It was hoped thereby to obtain criticism of the presentation of theory, to test the feasibility of using rotation properties in routine identification of ore minerals, and to determine what modifications of equipment are desirable. Thanks to the interest shown by the group, the hope proved well founded, and the results of the trial appear worthy of comment.

In class use, the most serious difficulties arose in determining dispersion formulas for minerals of weak dispersion. These difficulties have been traced to two causes: (1) failure to cross the analyzer and polarizer precisely, and (2) strain in the objectives used. If the mineral under observation is one of weak dispersion, a slight error in crossing the polarizer and analyzer may result in reversal of color fringes or in anomalous dispersion effects. If the objective is strained, failure to rotate the objective accurately to a strain-free position likewise gives incorrect results. If the objective in use is badly strained, proper adjustment is so difficult and time-consuming that weak dispersion effects are of limited use in mineral identification.

The subject of strain in objectives requires discussion. Green and the writer concluded that movement of isogyres and other distortions of polarization figures observed when the average objective is rotated are due to strain in the objectives. Mr. J. D. Reardon, of American Optical Company, and Mr. J. R. Benford, of Bausch and Lomb Optical Company, both experts in such matters, have confirmed this conclusion. The term "strain-free" as applied to objectives is relative. Objectives are classified as strain-free if the strain is below established limits of tolerance. The degree of strain permissible for objectives used in studying polarization figures is less than that for petrographic objectives.

A recheck of the dispersion formulas given for minerals of weak dispersion by Green and the writer indicates that certain of these are incorrect or doubtful. The minerals, with the revised dispersion formulas, are as follows:

Galena—DR_r essentially nil.
Sphalerite—DR_r essentially nil.
Magnetite—DR_r weak, $v > r$.

[1] Cameron, E. N., and Green, L. H., Polarization figures and rotation properties in reflected light and their application to the identification of ore minerals: Econ. Geol., vol. 45, pp. 719–754, 1950.

Cameron, E. N., The influence of the immersion medium on the rotation properties of anisotropic minerals in reflected light: Econ. Geol., vol. 46, pp. 68–75, 1951.

Franklinite—DR_r essentially nil.
Chromite—DR_r essentially nil.
Tetrahedrite—DR_r distinct, $v > r$.
Gersdorffite—DR_r essentially nil.
Argentite—DR_r essentially nil.
Hematite—DR_r essentially nil but probably $v > r$; DA_r distinct, $r > v$, as given.

The class trial showed that in describing strength of dispersion, it is best to use only three terms: negligible or essentially nil, distinct, and strong. The temptation to use supplementary terms—weak, low, moderate—is strong but should be resisted.

The descriptions of dispersion effects given above and in the paper by Green and the writer apply only to the effects seen with the particular optical set-up used; i.e., with air immersion and with a Spencer 4 mm, N.A. 0.85 objective. The writer now realizes that the dispersion effects seen are a function of several factors, two in particular. One is the aperture of the objective. In general, for a given immersion medium such as air, the lower the aperture of the objective the greater will be the spread of the isogyres for various wavelengths of light and the more distinct the color effects. We have found that in air a 37 ×, N.A. 0.65 objective gives best results. With objectives of lower aperture, the figures are too diffuse and the size of grain required is too great.

It is also true that if an anisotropic mineral is rotated to the 45-degree position, the separation of the isogyres due to rotation of incident light by the mineral will be the greater the lower the aperture of the objective. This permits somewhat more accurate measurement of small angles of rotation. Again, we find the 37 ×, N.A. objective best for this purpose.

A second factor influencing dispersion effects is the index of refraction of the immersion medium. The writer has already pointed out that the angle of rotation due to anisotropy of a mineral is a function of the index of refraction of the immersion medium.[2] In the same way, the strength of dispersion fringes and the amount of dispersion are functions of the index of the immersion medium. The writer's observations to date indicate that in oil having $n = 1.515$, color fringes of some opaque minerals are appreciably more distinct than in air. For hematite, for example, DR_r in oil is distinct, $v > r$.

The writer is experimenting with a special objective for use with an oil of $n = 1.637$. This has been furnished through the courtesy of Mr. Reardon. Studies are also being made with a 4.3 mm, N.A. 1.00, 40 × fluorite oil-immersion objective furnished through the kindness of Mr. Benford.

As quantitative measurements of dispersion require the use of monochromatic light, the writer asked Mr. Reardon to furnish filters that can be slipped into the vertical illuminator tube of the Spencer microscope between the field diaphragm and the polarizer in the extra space provided in the polarizer slot. A red filter (600–700 mμ) and a blue filter (400–450 mμ) have been provided. The red filter is satisfactory, but further experimentation is needed to secure

[2] Cameron, E. N., op. cit.

a satisfactory blue filter. An arc lamp is necessary with the present one, which has a low transmission.

As a result of the class trial, an error in the theory of polarization figures has been pointed out by Mr. Z. V. Jizba, one of the members of the class. In discussing the optics of reflected light, Berek[3] makes the following statement (pp. 15–16):

"Bei einer vollen Umdrehung des Kristalls in seiner Ebene treten, sofern der Anschliff anisotrop ist, in vier genau um 90° im Azimut voneinander unterschiedlichen Lagen Minimalwerte der Intensität auf; diese Azimute entsprechen genau den Normallagen des Anschliffs, d. h. denjenigen Lagen, in welchen die Schwingungsrichtungen der in den Kristall eindringenden Wellen parallel zu denen der Nicols liegen. In den vier 45° hiervon abstehenden Azimuten treten Maxima der Intensität auf; sie entsprechen den Diagonalstellungen der Schwingungsrichtungen mit Bezug auf die der Nicols. Keine Normallage ist intensitätsmässig vor der anderen unterschieden, und ebenso sind die diagonallagen intensitätsmässig untereinander gleichwertig."

The writer took this to mean that "the rotation (due to anisotropy) is at a maximum when the section lies at 45° in either direction from an extinction position."[4] Mr. Jizba has demonstrated that this is not true, and calculations from Berek's formula 107[5] confirm this. In general the greatest rotation produced by a given section of an anisotropic mineral occurs when the section is rotated on the stage to a position a few degrees to one side or the other of the 45-degree position. The difference between this greatest rotation and the rotation at the 45-degree position will depend on the mineral species and on the crystallographic orientation of the section being observed.

In order to determine the true maximum rotation that can be produced by a mineral, it is therefore necessary, in the study of polished surfaces, to observe a number of diversely oriented grains of a mineral in a surface, find the position of greatest rotation for each grain, and measure the angle of rotation. If a sufficiently large number of grains is covered, the highest value obtained should equal the true maximum rotation for the mineral or should closely approximate it. For a uniaxial mineral, this true maximum value will be given by a section parallel to the *c*-axis. In practice, however, this is a tedious and time-consuming procedure and is unnecessary. The same section that gives the true maximum value of rotation will give at the 45-degree position the highest rotation that can be given by any grain of the mineral at this position. This maximum for the 45-degree position is fully as diagnostic as the true maximum value of rotation and requires only a single measurement of rotation for each grain observed. The procedure given by Green and the writer should therefore be followed as outlined. The theoretical basis, however, stands corrected. Mr. Jizba will discuss this and some related matters in a forthcoming article.

[3] Berek, M., Optische Messmethoden im polarisierten Aufflicht: Fortschr. der Miner., Krist., und Petrog., vol. 22, pp. 1–104, 1937.

[4] Cameron, E. N., and Green, L. H., op. cit., p. 731.

[5] Berek, M., op. cit., p. 75.

At present, the most serious limitation on the use of polarization figures in mineral identification is the lack of reference data on the rotation properties of the various species of opaque minerals. Studies of various groups of minerals aimed at providing the necessary data are now in progress in our laboratory, and it is hoped that the first results will be forthcoming in the near future.

EUGENE N. CAMERON.

GEOLOGY DEPARTMENT,
UNIVERSITY OF WISCONSIN,
MADISON, WISC.,
March 7, 1951.

DISCUSSIONS

Sir: The recent review of a book by Alan M. Bateman, "Psychical Physics —A Scientific Analysis of Dowsing, Radiestesia, and Kindred Divining Phenomena" by S. W. Tromp,[1] leaves the reader with the impression that he may endorse the claims of users of the ancient divining rod which has many modern varieties. In the study of underground water and in oil exploration, I have been brought into frequent contact with these characters, their claims, and their failures. There is one phenomenon which *alone* proves the error of their pretentions. In every instance they get no response from the object of search until they are directly above it regardless of depth. Now the slightest knowledge of physics suffices to show that all known forces, for instance electromagnetic waves including light, magnetism, attraction of static electricity, and gravitational attraction, radiate outward from their sources in all directions, the intensity decreasing with the square of the distance. Only where some man-made reflector is employed do we find beams, for instance a searchlight. These observed facts are so at variance with the claims of dousers, however sincere, that the absurdity of the whole subject is self-evident. For just what natural reflectors could occur which always concentrate some unknown radiation into a perfectly vertical beam? Moreover, should it be claimed that the reaction of the divining rod is due, not to a force but to an emanation of a substance, it should be recalled that many oil and gas seepages are not directly above their sources.

F. T. THWAITES.

WISCONSIN GEOLOGICAL SURVEY,
UNIVERSITY OF WISCONSIN,
MADISON, WISC.

[1] ECON. GEOL., vol. 45, pp. 591–592, 1950.

REVIEWS

Guidebook of the San Juan Basin, New Mexico and Colorado. VINCENT C. KELLEY, Editor. Pp. 153; figs. 26; tbls. and chts. 23; pls. 5. Published by the New Mexico Geological Society for its First Field Conference, November 1950. Obtainable from the Director, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Price, $5.00, payable to the New Mexico Geological Society.

The New Mexico Geological Society, a lively young organization that evidently represents diverse interests within the profession, held its First Field Conference in the San Juan Basin during the period November 3–5, 1950. The route of travel, though long in terms of the daylight hours available, was found to furnish a highly satisfactory sample of geologic features along the east and north sides of the basin. These features are described succinctly in the Conference guidebook, which also contains much supplementary information in the form of summary statements, topical discussions, and numerous illustrations.

The book was conceived and prepared within the amazingly short period of three months, chiefly by representatives of the U. S. Geological Survey, the New Mexico School of Mines, and the University of New Mexico. It is essentially two-fold in organization, and comprises a series of well detailed, carefully annotated road logs and a collection of 19 summary papers that add materially to the value of the book. The logs are drawn up in standard form, and include location data that are adequate without being overwhelming. Brief descriptions of many features, both geologic and non-geologic, are included.

The individual papers, which provide an excellent regional background for the geologist, are surprisingly varied in scope. Many will appeal primarily to the petroleum geologist, but they also contain information that should interest men working in other fields. Stratigraphic relations are discussed in some detail, with emphasis on the pre-Tertiary parts of the section, and some controversial issues are outlined and reviewed. Other papers deal with the Precambrian rocks, regional structure, selected local structural features, coal resources, geophysical exploration, drilling practices, and the occurrence, production, and marketing of oil and gas. Maps, sections, and charts are effective supplements to this diverse text. The main geologic map, a very readable compilation from several sources of data, is worthy of particular note.

The book is not without shortcoming. Several typographical errors, some awkward and even ambiguous phraseology, and two discrepancies between road-log text and maps probably are results of the very short "gestation period" available to the editorial staff prior to the field-trip deadline. A simplified columnar section for the region, placed at the end of the Introduction, would have made the road-log data much clearer to the average reader. Some of the illustrations could have been improved by reduction to smaller size, had the lettering been made larger on the original copy. Although they are surprisingly well integrated, the contributions by individual authors represent different approaches, types of coverage, and degrees of detail with respect to the topics treated. Few of these differences are serious,

although critical editing might well have been aimed at such sections as the lengthy list of "selected references" on Triassic rocks, which list appears to lack some elements of selectivity.

The book, with its loose-leaf form and plastic ring binder, resembles several other geologic guidebooks published during recent years. Both the text and illustrations are printed on linen-finish paper of exceptional quality, and the printing itself, done by offset methods, is unusually clear and uniform in appearance.

The editor and his co-workers are to be congratulated on their success in bringing together, in such usable form, a wide variety of geologic information, much of which is not readily available elsewhere. The reviewer, in purchasing his own copy of this book, finds himself impressed all over again with a region of great geologic interest and of scenery that, in the words of the editor, "will certainly please visitors from Texas and other plains states and in places might even thrill those from California."

RICHARD H. JAHNS.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA 4, CALIF.

Einfuehrung in die Mineralogie, Kristallographie und Petrologie. By C. W. CORRENS. Pp. 414; figs. 405; pl. 1. Springer-Verlag, Berlin, 1949. Price, DM 41.60 bound, 38.00 paper.

This noteworthy book resulted from the need for a reference emphasizing the essential unity of mineralogy, crystallography, petrology, and related sciences. It is not intended to replace or duplicate normal elementary textbooks in any of these fields, but rather to integrate and extend their study. The two main parts of the book are Crystallography (mathematical, chemical, physical, and crystal-growth sections) and Petrology (physical-chemistry, magmatic differentiation, weathering, sedimentation, metamorphism, and geo-chemical conclusions); an Appendix includes tables of crystallographic information, mineral properties, rock names and compositions, and references. The longest table lists the following properties for each of 300 mineral species: name, formula, space group and size of unit cell, crystal habit, cleavage, hardness, density, color, streak, refractive indices and luster, optic axial angle, optic orientation, pleochroism, and occurrence.

The book preserves a remarkably high level of excellence throughout. Important concepts are covered in a fine, well-illustrated exposition. Although this book may be too advanced for some students, it should gain wide recognition for bridging the gap between elementary mineralogy and the several advanced phases of the subject.

HORACE WINCHELL.

Das Polarisationsmikroskop. By CONRAD BURRI. Pp. 308; figs. 168; pls. 4. Lehrbücher und Monographien aus dem Gebiete der exakten Wissenschaften. Chemische Reihe. Band V. Verlag Birkhäuser, Basel, 1950. Price, Suisse Francs 30.10.

This new text provides a modern treatise on optical mineralogy including not only the elementary material found in most textbooks but also material bridging the gap between the elementary texts and the mathematical-physical treatments in the journals. Emphasis is given to the following topics: elementary crystal optics, use and construction of the microscope, special techniques, and practical methods. The reflecting microscope is not considered; determinative tables and descriptions of minerals are also not included.

Explanations are clear, concise, and accurate, and they are based on modern concepts of optical theory. The treatment of the practical side of the subject is more extensive and more usefully developed than in most texts of optical mineralogy. In the opinion of the reviewer this is the best textbook on the subject that has appeared in the past 40 years.

GEORGE J. NEUERBURG.

UNIVERSITY OF CALIFORNIA,
LOS ANGELES, CALIF.

Petroleum Geology. By KENNETH K. LANDES. Pp. 660; figs. 222; tbls. 2. John Wiley & Sons, Inc., New York, 1951. Price, $10.00.

Members of the geology profession and those interested in the petroleum industry will welcome this new and much needed text book on petroleum geology. The teaching profession particularly will find immediate need for it. Voluminous as is the literature on petroleum geology, and despite many reference books, it is rather surprising that there are so few usable text books. Emmons' "Geology of Petroleum" is much out of date and Lalicker's "Principles of Petroleum Geology" devotes only 125 pages out of 365 to presentation of principles and theoretical phases, the remainder being descriptions of oil fields. This new volume devotes 324 pages out of 660 to principles and processes.

This volume, following an introductory chapter that includes a brief history of petroleum, is divided into 3 parts: Part I, Exploration and Exploitation; Part II, Geologic Occurrence of Petroleum; and Part III, Present and Future Oil Supplies. Part I, of two chapters, deals with surface and subsurface exploration, geophysical methods, drilling, sampling, mapping and exploitation procedures and practices.

Part II, with chapters 4 to 8, treats of the Physical and Chemical Properties of Petroleum, The Origin and Evolution of Oil and Gas, Migration of Oil and Gas, and Accumulation. Under Origin is considered the source of hydrogen and carbon, time of generation, sedimentation, biochemical activity, burial, dynamochemical activity, post-burial changes, evolution and metamorphism of petroleum, and the origin of natural gas. Migration includes discussions of all of the later theories regarding this knotty problem, with considerable attention to the distance and direction of migration. Two chapters on Accumulation treat of reservoir rocks and the various kinds of traps. This last part includes many full page illustrations with legends a page or so in length, in which much of the text has gone into the legend. They are effective presentations, nevertheless. There is an excellent section on finding of stratigraphic traps.

Part III, on Oil Supplies, consists of three chapters; the first, and the longest chapters of the book (185 pages), deals with the distribution of oil and gas fields of the United States taken up state by state, rather than by the familiar regional divisions such as Gulf Coast or Midcontinent. The individual fields or sections of each state are described and illustrated separately. The following chapter deals with oil regions outside of the United States, country by country. The concluding chapter deals with future oil supplies, with discussions of known reserves, undiscovered reserves, and technologic reserves. An appendix covers two pages on "The Literature of Petroleum Geology."

This is the most comprehensive text book on petroleum that has yet appeared. It is well balanced, with adequate attention to discussion of principles and theory, and is excellently and abundantly illustrated. It will also make a valuable reference book for anyone who wishes to look up the present status of thought regarding the principles of petroleum geology, or technology or data regarding any of the

oil fields or oil regions of the world. It should immediately win first place as a text book for the teaching of petroleum geology.

ALAN M. BATEMAN.

Marine Geology. By PH. H. KUENEN. Pp. 568; figs. 246; pls. 2; tbls. 28. John Wiley & Sons, Inc., New York, and Chapman & Hall, Ltd., London, 1950. Price, $7.50.

The title of this book immediately attracts one's attention and as one browses through it his attention is quickened. The book was written to summarize present knowledge and views held on controversial matters in the field. It deals with submarine land forms and their interpretation, atolls, and the sediments on the sea bottom. It is not so much a collection of data but a discussion of problems and relations written in a stimulating manner.

The chaptear headings convey an idea of the subjects covered. They are: Physical Oceanography, Sea Basins (shapes and evolution), Indonesian Deep-Sea Depressions (origin and comparison with others), Sources and Transportation of Marine Sediment, Formation of Marine Sediments (environments, classification, and distribution), Coral Reefs, Geomorphology of the Sea Floor, and Eustatic Changes of Sea Level.

The author states he had three purposes in mind, (1) to introduce this subject to students of geology, (2) to provide a guide for geologists, oceanographers, and scientists in general, and (3) to aid advance in research by summarizing results and emphasizing problems to be solved. All these the author seems to have done very successfully. His discussion of the Indonesian Depressions reveals his own personal knowledge of the area and its problems.

Professor Kuenen is Head of the Geological Department at the University of Groningen and Director of the Foundation for Marine Geology at that institution.

Terrestrial Magnetism and Electricity. Edited by J. A. FLEMING, under auspices of the National Research Council. Pp. 794; figs. 296; tbls. 32. Dover Publications, Inc., New York, 1950. Price, $4.95.

This volume is a reprinting with corrections of the 1939 edition. It contains all findings of modern geophysics in the field of terrestrial magnetism assembled in one large volume. This serves as the reference in this field for "practical scientists and technicians in radio, mining, astronomy, physics, geophysics, engineering, meteorology, and navigation." It is the most authoritative and comprehensive volume on the subject.

Soils, Their Origin, Constitution, and Classification—An Introduction to Pedology, 3rd Edit. By GILBERT WOODING ROBINSON. Pp. 573; figs. 22; pls. 9. John Wiley & Sons, New York, and Thomas Murby & Co., London, 1949 (1951). Price, $5.00.

The first edition of this well-known soils book appeared in 1932, the second in 1937 and the third in 1951. The last, like its predecessors, is a comprehensive view of the study of soils.

The first section treats of the constitution, formation, clay complex, base exchange, organic matter, physical properties, and water relationships. The next section (in 7 chapters) deals with the chief soil groups of the world and their classification, then follows geographic distribution, soil surveys, soil analyses, and Soils,

Plant Growth, and Agriculture. Much new material has been added, particularly that dealing with soil chemistry, the part played by clay fractions, and the relation of soils to plant ecology.

The book will be as useful as the earlier editions to students of soils and to geologists.

BOOKS RECEIVED.

CHARLES H. SMITH.

Library of Congress—Washington 25, D. C., August–December 1950.

Korea—An Annotated Bibliography of Publications in Western Languages. Compiled by HELEN D. JONES AND ROBIN L. WINKLER. Pp. 155. Price, $1.10.

Korea—An Annotated Bibliography of Publications in the Russian Language. Compiled by ALBERT PARRY, JOHN T. DOROSH, AND ELIZABETH G. DOROSH. Pp. 84. Price, 65 cts.

Korea—An Annotated Bibliography of Publications in Far Eastern Languages. Compiled by EDWIN G. BEAL, JR., AND ROBIN L. WINKLER. Pp. 167. Price, $1.15.

Indochina—A Bibliography of the Land and People. Compiled by CECIL C. HOBBS, GRACE H. FULLER, HELEN D. JONES, JOHN T. DOROSH, AND I. MILTON SACKS. Pp. 367. Price, $2.50. *References to works on physical setting, history, culture, and socio-economic and political development of Indochina.*

Summary of Water-Flooding Operations in Illinois, 1950. FREDERICK SQUIRES ET AL. Pp. 40; figs. 27; tbl. 1. Illinois Geol. Survey Circ. 165, Urbana, 1950. *31 controlled operations as of January 1, 1950.*

The Kansas Rock Column. RAYMOND C. MOORE, JOHN C. FRYE, J. M. JEWETT, WALLACE LEE, AND HOWARD G. O'CONNOR. Pp. 132; figs. 52. Kansas Univ. Geol. Survey Bull. 89, Lawrence, 1951. *A generalized composite section of rocks occurring above the Precambrian basement rocks is presented with classification and nomenclature used by the Kansas Geological Survey. Includes graphically represented selected measured sections and well logs for most parts of column and summaries of areal distribution of major rock units.*

Surface Waters of Mississippi. Under direction of IRVING E. ANDERSON. Pp. 338; figs. 10; pls. 3. Mississippi Geol. Survey Bull. 68, University, 1950.

Ohio's Mineral Resources. IV. Foundry Sand. DOUGLAS C. WILLIAMS. Pp. 22; tbls. 5; figs. 33. Ohio Univ. Studies Eng. Ser. Vol. XIX, No. 6, Circ. 53, Columbus, Nov. 1950. Price, 50 cts. *Mechanical and chemical analyses of sand samples, and paper on the fragmentation of sand grains during the mulling operation.*

Bibliography of the Geology of the State of South Carolina. JULIAN J. PETTY. Pp. 86. South Carolina Univ. Pub. Bull. 1, Columbia, 1950.

Laboratory Manual for Mineralogy. STANLEY REICHERT. Pp. 234. Wm. C. Brown Co., Dubuque, Iowa, Dec. 1950. *Outgrowth of mimeographed notes in use by Mineralogy Department at the Colorado School of Mines. Includes the more common minerals and emphasizes their diagnostic physical properties. Many typographic errors.*

Geology and Mineral Deposits of the Zeballos Mining Camp, British Columbia. JOHN S. STEVENSON. Pp. 145; figs. 43; pls. 15. British Columbia Dept. Mines Bull. 27, Victoria, 1950. *Gold-bearing quartz veins in quartz diorite. Also high temperature replacement deposits in limestone, with copper, iron, and gold. Magnesian limestone is of potential economic interest. A detailed study of the petrography, structure, and mineralization accompanied by descriptions of the properties.*

Geology of Osway Township. W. W. MOORHOUSE. Pp. 27; photos 4; maps 7, including colored map, scale 1″ = 1,000′. Ontario Dept. Mines 58th Annual Rept., Vol. LVIII, Pt. V, 1949, Toronto, 1951. *Keewatin volcanics, Timiskaming sediments cut by Algoman granite and related intrusives. Gold mineralization occurs along greenstone-sediment and porphyry-sediment contacts. The area was actively prospected in the early nineteen forties.*

Quebec Department of Mines—Quebec, 1950.

Geol. Rept. 42. Pt. I. North Shore of the Saint-Lawrence from Mingan to Aguanish, Saguenay County. W. WARREN LONGLEY. Pp. 27; pls. 16; colored map, scale 1″ = 1 mi. *General, structural, and economic geology described. Minor mineralization.* **Pt. II. Limestone Deposits of the Mingan Islands Area, Saguenay County.** G. W. WADDINGTON. Pp. 13; tbl. 1; pls. 4; map 1. *Substantial amounts indicated with generally low magnesia content.*

Geol. Rept. 44. Cawatose Map-Area, Pontiac County. WILLIAM G. WAHL AND F. FITZ OSBORNE. Pp. 37; figs. 3; pls. 5; 1 colored map, scale 1″ = 1 mi. *Area lies within Grenville sub-province, about 20 miles south of Temiscamian sub-province. Dominantly gneisses, with little limestone and quartzite of typical Grenville aspect, intruded by syenite, pegmatite stringers and basic dikes.*

Report of the Great Britain Geological Survey Board for the Year 1949. Pp. 18. London, 1950.

The Australian Mineral Industry—Economic Notes and Statistics, Vol. 3, No. 2. Pp. 30. Melbourne, 1950. *Paper on gypsum in Australia; statistics.*

Progress of the Geological Survey of India. W. D. WEST. Pp. 19. Delhi, 1947. *History of its development and achievements.*

Principal Clay Deposits of Hyderabad State. SYED KAZIM, L. S. KRISHNA MURTHY, AND K. VENKATESWARA RAO. Pp. 52; pls. 3; tbls. 26. Hyderabad Geol. Ser. Bull. 7, 1950. *Geology of the deposits; physico-chemical properties of the clays.*

Minerales No. 35. Pp. 45. Inst. ing. Chile Rev., Santiago, 1950.

Departamento Nacional da Produção Mineral—Rio de Janeiro, 1948–1949.

Bol. 30. Ensaios de Beneficiamento de Minérios. JAYME B. DE ARAUJO, JOSÉ GUILHERME DE CARVALHO, ROBERTO BORGES TRAJANO, AND HAROLDO BRAGA CRUZEIRO. Pp. 95. *Papers on mineral beneficiation—concentration of combustible matter contained in charcoal fines and coke breezes, recovery of cassiterite from greisen, concentration of monazite, treatment of beach sands to be used in glass manufacturing, and the removal of hematite from beach sand.*

Bol. 31. Ensaios de Beneficiamento de Minérios. Roberto Borges Trajano, Jayme B. de Araujo, and Orlando de Faria Carvalho. Pp. 91. *Papers on mineral beneficiation—treatment of gypsum, recovery of KCl, recovery of gold from quartzite, concentration of tungsten, treatment of pegmatite to show if it could be used in ceramic whitewares.*

Bol. 32. Relatório da Diretoria, 1947. Mário da Silva Pinto. Pp. 100.

Bol. 33. Análises de Calcários e Indústria de Cal no Brasil. Jorge da Cunha, J. Epitacio P. Guimarães, Benedito Alves Ferreira, and Benedito Roquete. Pp. 369. *Chemical analyses of limestone and dolomite occurrences, detailed descriptions of the lime industry in Brazil and related information.*

Service des Mines de Madagascar—Paris, 1949.

Fasc. XVIII. Les Dépôts Lacustres Pliocènes-Pléistocènes de l'Ankaratra, Madagascar. André Lenoble, E. Manguin, Edouard Boureau. Pp. 137; numerous illustrations. *Pliocene-Pleistocene lake deposits of l'Ankaratra, their diatoms and flora, described. Basins contain an estimated 40,000,000 tons of lignite, and also uranium mineralization.*

Explanation Notes on the Iakora Sheet; Vondrozo Sheet; Farafangana Sheet; Vangaindrano Sheet; Ranotsara Sheet; South Midongy Sheet. Henri Besaire. *Each of the above mentioned contains from 8 to 14 pages describing briefly the rock types, structure, and economic minerals, and a colored geological map, scale 1/200,000.*

Comptes Rendus du Congrès Scientifique, Elizabethville, 1950. Pp. 180. Comité Spécial du Katanga, Bruxelles, 1950. *Papers on social problems and conditions among the native population.*

La Teoria dell'Impounding di R. A. Mackay nei Riguardi di Alcuni Giagimenti Piombo Zinciferi delle Alpi Orientali. Dino Di Colbertaldo. Pp. 35; figs. 5. Pavia, 1949. *The "impounding" theory of R. A. Mackay is applied to 4 lead-zinc ore bodies and found to fit several of them. The influence of organic substances on deposition is indicated also.*

Annales de la Société Géologique de Pologne, Vol. XIX, Fasc 4. Pp. 58. Cracow, 1951. *Papers on the southwest border of the platform of eastern Europe between the Baltic and the Carpathians, Miocene bryozoans of Benczyn, slip-bedding in the Carpathian Flysch, and excursion guides to the reunion of the Geological Society of Poland.*

Muséum d'Histoire Naturelle du Pays Serbe—Belgrade, 1948–1949.

Ser. A, Livre 1. Pp. 117. *Papers on the barite mines of Treťca, discovery of chalcophanite, structure, and paleontology.*

Ser. A, Livre 2. Pp. 183. *Papers on microscopic examination of lead-zinc ores of the Kucaňna mines, the age of the higher Upper Cretaceous of the Tampico embayment in Mexico as an example of the world-wide existence of microfossils, other papers on stratigraphy and paleontology.*

Annals of the University of Stellenbosch, Vol. XXVI, Section A, Nos. 3–11. Pp. 507; numerous illustrations. Cape Town, 1950. Price £1'1'0. *Nine interesting papers.* **Aspects of the Geology of the Northern Soutpansberg Area.** J. S. van Zyl. *Oldest rocks are sedimentary invaded by basic magma which yielded anorthosite, amphibolites, serpentines, chromite, corundum. These are*

cut by granite and overlain by clastics and basalts intruded by diabase. Chromite and corundum occur along definite horizons in anorthositic rocks. **The Geology, Structure and Petrology of the Nuwerus Area, Cape Province.** W. C. BRINK. *Detailed petrographic descriptions of norites, granites, and metamorphic rocks, discussion of perthites and myrmekite and a criticism of deductions concerning contamination of granite by country rock based on chemical analyses only.* **The South African Pyrophyllite Deposits.** C. T. POTGIETER. *Mode of occurrence, petrography and genesis of South African deposits. Maribogo pyrophyllites are talc derived from altered xenoliths of hornblende schist. Deposit in Worcester district is attributed to leaching of alkalies, magnesia, and iron, accompanied by alumina enrichment and little variation in silica content of enveloping shale.* **The Geology and Chemistry of the Laingsburg Phosphorites.** H. C. STRYDOM. *Conditions of deposition of Upper Dwyka Shales containing the phosphorite lenses and nodules; the author believes deposits were laid down in shallow waters of an estuary or floodplain, where anaerobic bacterial action predominated in the chemical precipitation of tri-calcium phosphate. Seas enriched in phosphoric acid and fluorine, the latter effecting the deposition and preservation of the former.* **The Dolerite Intrusions of the Wellington-Moorreesburg Area.** Q. C. BOUMAN. *Petrography, metamorphism and chemistry of the dolerites described, with 15 new chemical analyses.* **A Comparative Petrographic Study of the Sediments of the Rooiberg and Stavoren—Vlakfontein Areas.** M. R. HENZEN. *Applying the grain-count-percentage and elongation-index-frequency methods, it was found that quartzites in two areas had dissimilar provenances.* **The Structure and Petrology of the George Granite Plutons and the Invaded Pre-Cape Sedimentary Rocks.** C. T. POTGIETER. *Detailed description of stratigraphy, granite, dolerite, metamorphism and structure.* **Morphological Aspects of the Bokkeveld Series at Wuppertal, Cape Province.** B. SWART. *Description of a sandstone and shale series, its structure, fossils and heavy minerals, and a reconstruction of the environments in which the rocks of the Cape System in Western Cape Province were laid down.* **The Complex Dioritic Stocks West of the Malmesbury-Paardeberg Granite Pluton.** P. J. VAN ZYL. *Petrography, chemistry, phase petrology, petrogenesis are described. Diorites form a sequence of successive intrusions with enrichment in ferrous iron and gradual decrease in anorthite content.*

SCIENTIFIC NOTES AND NEWS

The U. S. Atomic Energy Commission needs experienced geologists and mining engineers in its Raw Materials Operations. Positions are located in New York City and in Grand Junction, Colorado. Beginning salaries from $4,600 (GS-9) to $8,800 (GS-14), depend on experience. Minimum experience three years. Civil status not required. Those interested should write to U. S. Atomic Energy Commission, 70 Columbus Avenue, New York 23, N. Y., attention Mr. Robert D. Nininger, Raw Materials Operations.

The Commandant Charcot, ship of the French Polar Research Expeditions, taking advantage of the breaking up of the Antarctic ice pack, landed fourteen French scientists and an Australian glaciologist at Port-Martin (66° 50′ S by 141° 25′ E), Adélie Land, on January 9. This group will relieve the party of eleven which has just completed a first year of research, weathering the six-month Antarctic night in gale-proof barracks brought from France. Two members of the first over-winter party will remain a second year. In addition to meteorological and hydrographic studies, the French scientists are exploring the mysterious hinterland of Adélie Land with dogsleds and vehicles with caterpillars. Meantime, at the other end of the world, in the center of the Greenland Ice Cap, nine other members of the French Polar Research Expeditions are continuing their weather research at the Central Ice Cap Research Station (70° 54′ N by 40° 42′ W) at an altitude of 9,900 feet in temperatures of − 65° to − 80°. For nineteen continuous months the Central Ice Cap Station has taken four daily weather observations which are incorporated into the International Weather Network. Director of the Arctic and Antarctic expeditions is Paul E. Victor, Arctic explorer and ethnographer.

R. A. MACKAY has just returned to London from a short visit to Uganda.

J. ROBERT VAN PELT, mining engineer and research executive of Columbus, Ohio, has been named president of the Montana School of Mines at Butte and took office the first of April.

W. T. IRVINE has been made senior mine geologist for Consolidated Mining & Smelting Company of Canada, Ltd. He will have charge of all the company's operating mines in British Columbia, except the Sullivan.

R. G. MCEACHERN has been appointed assistant to the chief geologist for Consolidated Mining & Smelting Co. of Canada.

HAROLD M. WRIGHT, metallurgical engineer of Vancouver, B. C., is the new chairman of the British Columbia section of the Canadian Institute of Mining & Metallurgy for 1951.

C. A. ANDERSON, of Prescott, Ariz., will head the geological survey section of the Defense Minerals Administration's field office at Tucson.

J. PARNELL CAULFIELD, formerly general manager of the Hudson Bay Mining & Smelting Co., Ltd., operations at Flin Flon, Canada, has resigned and is now general manager of the Utah division, Kennecott Copper Corporation.

The Ground Water Branch, Water Resources Division, U. S. Geological Survey, announces the following activities and changes in personnel: MAURICE L. BRASHEARS, JR., of the Mineola, N. Y. office, has been assigned for several months as a Visiting Expert Consultant on Water Supplies to the Supreme Commander of the Allied Forces in the Pacific and to the Japanese Government. NORBERT J. LUSCZYNSKI is Acting Engineer in Charge of the Mineola office during Mr. Brashears' absence. JOSEPH W. BROOKHART, of the Salisbury, Md., office, has been given charge of the comprehensive ground-water investigations on the Island of Guam with assignment for at least a year, probably longer. THEODORE ARNOW, of the Mineola, N. Y., office, left for the Trust Territory to work with the Navy's program for the investigation of water supplies in the several islands. WILLIAM F. GUYTON, engineer of the Washington office since July 1939, and recently Chairman of the Water Utilization Committee, resigned December 15, 1950. In January 1951, he and WALTER N. WHITE, formerly District Engineer in charge of ground-water investigations in Texas, with 37 years service with the Geological Survey, opened offices as Consulting Ground-Water Hydrologists at 307 West 12th St., Austin 1, Texas, with a branch office at 10 Mississippi Ave., Silver Spring, Md. FRED H. KLAER, JR., for the past 9 years Geologist in Charge of ground-water investigations in Indianapolis, Ind., resigned on February 9, 1951, to accept a position with the Ranney Well Construction Company, Columbus, Ohio. GORDON E. DAVIS, engineer, is taking charge of the Indiana work at the present time. MICHAEL D. CHRONOPOULOS, LEONIDAS D. CORTESSIS, and PRAXITELIS A. ARGYROPOULOS, Hydraulic Engineers from Greece, have recently completed a 3-month period of in-training in ground-water and surface-water hydrology with the U. S. Geological Survey. G. C. CHATERJI, Ground-water Geologist of the Geological Survey of India, arrived in the United States September 12, 1949, on an in-service training grant. He visited 29 field offices of the U. S. Geological Survey, Water Resources Division where he became an integral member of the staff and by participating actively and directly in this manner, he became thoroughly acquainted with the various methods and techniques developed by the Geological Survey in the pursuance of the study of water resources in the United States. He left in February, 1951, for India. ROLAND DEBLOIS, a Geologist of the Geological Surveys Branch, Department of Mines, Quebec, Canada, arrived in Washington in 1951 to study the methods and work of the Ground Water Branch. Mr. DeBlois will be in the United States for three or four months and will work with Mr. P. E. LaMoreaux, Geologist in Charge, U. S. Geological Survey, Tuscaloosa, Alabama. LESLIE E. KENT, Geologist, Geological Survey, Department of Mines, Union Government of South Africa, is studying in the United States, under a Commonwealth Fund Fellowship, for twelve months, on a number of research projects, among them four categories of hydrologic research.

WILLIAM D. JOHNSTON, chief of the U. S. Geological Survey's foreign geology branch, has returned from India. Dr. Johnston represented the United States Government and the Geological Society of America at the centenary of the Geological Survey of India in Calcutta, conferred with governmental, industrial, and scientific leaders on Point Four geological projects. He reported that India is keenly interested in the possibility of sending native geologist trainees to the United States under both Point Four and United Nations provisions. To work on a cooperative Point Four manganese investigative project in Orissa, JOHN A. STRACZEK, minerals geologist, left Washington March 18, for Calcutta. GEORGE C. TAYLOR, ground-water geologist, began work there in January on ground-water resources problems. In addition to attending the Indian Geological Survey centennial celebrations, Dr.

Johnston participated in the Indian Science Congress in Bangalore, in meetings of the subcommittees on iron and steel, and industry and trade, of the United Nations Economic Committee for Asia and the Far East at Lahore, and other conferences in India and Pakistan.

WILSON D. MICHELL has left the employ of the Resurrection Mining Company, Leadville, Colo., to join the staff of the Reynolds Jamaica Mines, Ltd., as chief geologist in connection with the development of bauxite deposits in Jamaica.

H. R. RICE, for the past three years Associate Editor of the Canadian Mining Journal, has been appointed Editor, succeeding R. C. Rowe, who has been Editor since 1928 and who will continue his interest as Editor in Chief.

B. R. MACKAY, of the Geological Survey, Ottawa, was Canadian delegate to the Centenary of the Geological Survey of India held in Calcutta during January.

R. V. PORRITT has been appointed General Manager for Noranda Mines, Ltd., succeeding H. L. ROSCOE.

ALLEN W. PINGER, formerly geologist for the New Jersey Zinc Co., at Franklin, N. J., has resigned. He has moved to Salt Lake City, Utah, where he will continue doing geological and geophysical work on a part-time basis with New Jersey Zinc Exploration Co. He also plans to do consulting work.

D. F. HEWETT has returned from California for a visit to Washington and the East.

MEAD LEROY JENSEN, of the Massachusetts Institute of Technology, has been appointed Instructor of the Department of Geology at Yale University.